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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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂-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
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U.S. Department of Energy

PREFACE

If the concentration of carbon dioxide (CO₂) 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 CO₂ Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health and Glaciers, Ice Sheets, and Sea Level: Effect of a CO₂-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

CONTENTS

EXECUTIVE SUMMARIES	1
GLOSSARY OF TERMS	51
TABLES	63
GLOSSARY OF ACRONYMS	65
INDEX OF COMMON NAMES	73
INDEX OF SCIENTIFIC NAMES	75
CITATION INDEX	77
SUBJECT INDEX	95

EXECUTIVE SUMMARIES

ATMOSPHERIC CARBON DIOXIDE AND THE GLOBAL CARBON CYCLE

Carbon dioxide (CO₂) 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 CO₂ 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 CO₂ measurements in 1958, during a period of unprecedented fossil fuel use. A doubling of the atmospheric CO₂ level of 1800 may produce a global average temperature warmer than during any period in the last 100,000 years or more, and the CO₂-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 CO₂ sources and sinks, which determines the rate of increase in the atmospheric CO₂ concentration. The observed increase in CO₂ 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 CO₂ concentration as fossil fuel use continues. The carbon reservoirs that are known to be important in the response to anthropogenic CO₂ are the atmosphere, the ocean, and the terrestrial biosphere including soils.

Predictions of future atmospheric CO₂ 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 CO₂ 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 CO₂ levels that are inconsistent with the historical atmospheric CO₂ increase. This inconsistency implies that significant errors in projections are possible using current carbon cycle models.

Detailed histories of atmospheric CO₂ obtained from ice cores indicate that significant nonfossil CO₂ 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 CO₂, long before land-use changes and fossil fuel burning by humans began. Over the past 100 million years, atmospheric CO₂ levels are thought to have been regulated primarily by the balance between (1) CO₂ releases from biogenic carbonate precipitation in the ocean and from tectonic processes and (2) CO₂ 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 CO₂ 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 CO₂ 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 CO₂

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ (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 CO₂ 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 CO₂ measurements network is now documenting a global concentration increase, at an annual rate averaging 1.5 ± 0.2 ppm (3.2×10^{15} g C). The atmospheric increase since 1958 represents an amount equivalent to $58 \pm 5\%$ of the total fossil fuel CO₂ 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 CO₂ 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 CO₂ 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 CO₂ variations over the past 200 years, but current uncertainties still do not permit an adequate definition of the magnitude and timing of either nonfossil CO₂ 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 CO₂ record itself.

FOSSIL FUEL CO₂ EMISSIONS AND RESOURCES

Global emissions of CO₂ from fossil fuels increased regularly at a 4.4% annual rate from an estimated release of 1.6×10^{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 (~ 5×10^{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 ($\sim 4000 \times 10^{15}$ g C) that it is highly likely that large quantities will be utilized and that much higher atmospheric CO₂ concentrations will result in time. Refining current estimates of these resources is deemed unlikely to have an appreciable effect on uncertainties in atmospheric CO₂ 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 CO₂ BY THE OCEANS

The oceans, particularly the areas of open ocean, have been the most important sink for anthropogenic CO₂. Knowledge of oceanic processes that determine CO₂ 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 CO₂ uptake. These include naturally occurring tracers and transient tracers such as chlorofluorocarbons, tritium, bomb-¹⁴C, and excess carbon.

Given the intricacies of ocean circulation, chemistry, and biology, credible estimates of CO₂ uptake can come only from models. The relatively simple, one-dimensional (depth) models initially developed do not take up enough anthropogenic CO₂ to accurately account for known releases and, thus, produce higher concentrations of CO₂ in the atmosphere than was historically the case. Models of intermediate complexity, initial two-dimensional formulations, have generally taken up no more CO₂, 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 CO₂ uptake. Enhanced carbon storage on continental shelves (0.2×10^{15} to 0.8×10^{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 CO₂ 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.

CO₂ EXCHANGE BETWEEN THE ATMOSPHERE AND TERRESTRIAL SYSTEMS

The net release of carbon to the atmosphere from deforestation in 1980 is currently estimated at 0.6×10^{15} to 2.6×10^{15} g. Longer term calculations indicate a net release of 90×10^{15} to 180×10^{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 CO₂ uptake. The total mass of organic carbon in the world's terrestrial biota and soils ($\sim 2000 \pm 400 \times 10^{15}$ 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 CO₂ 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 CO₂ 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 0.2×10^{15} to 1×10^{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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 10¹⁵ g C/year remains a basic, unresolved issue—one which must be addressed to understand the impacts of increasing CO₂ 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 CO₂ 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 CO₂ uptake, climate, and ocean circulation. Lack of relevant field data is the principal obstacle to this understanding. Rethinking of current atmospheric CO₂ reconstructions and of the omission of a land-ocean interface in models is also indicated.

MODELING FUTURE GLOBAL ENERGY AND CO₂ EMISSIONS

The principal uncertainty governing atmospheric CO₂ levels a century from now appears to be the future rate of fossil fuel CO₂ 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 CO₂ emissions likely in the absence of explicit control policies or feasibility studies that assess patterns of energy and economic growth consistent with explicit CO₂ emissions constraints. Differences in structure and basic assumptions among current emissions models, however, are such that the key factors in CO₂ 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 CO₂ 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 CO₂-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 CO₂ emissions. Prior to 1980, published studies reported annual rates of growth in CO₂ 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 CO₂ emissions are possible if energy conservation and shifts to CO₂-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 CO₂ 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 CO₂ emissions now appear to be possible even without explicit policy intervention. The field of policy analysis has remained largely unexplored.

PREDICTING FUTURE ATMOSPHERIC CO₂ LEVELS

The appearance of high uncertainty in *modeled* fossil fuel emissions and the seemingly high contributions to uncertainty in future atmospheric CO₂ 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 CO₂-climate responses for high-CO₂-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/CO₂ 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 CO₂ levels. Despite this, atmospheric CO₂ 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 CO₂ level before 2025 now seems highly unlikely, and doubling may not even occur within the next century.

Projections of future atmospheric CO₂ 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 CO₂ 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 CO₂ 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 CO₂-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 CO₂-climate changes. However, projections of CO₂ 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 CO₂.

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ fluctuations, CO₂-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 (CO₂) 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, CO₂ plays an important role in maintaining the Earth's moderate climate. Mankind's activities have inadvertently increased the atmospheric concentrations of CO₂ and other gases present in trace amounts (e.g., the CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ absorbs radiation that is emitted upward by the Earth's surface and by gases lower and higher in the atmosphere; CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentration would occur in summer and the minimum in winter. Various model calculations of these quantities agree to within about $\pm 10\text{--}15\%$.

Changes in ozone (O₃), 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 O₃ balances the emission of infrared radiation by CO₂ 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 (CH₄), nitrous oxide (N₂O), and two chlorocarbons (CFC₁₃ and CF₂Cl₂). Many of the trace gases have band strengths that are greater than the band strength of the 15- μm CO₂ band, but because of their small concentrations, these

gases do not have radiative effects as large as that of CO₂. 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 CO₂ concentration.

Projections of the radiative effects of CO₂ 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 CO₂ 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 CO₂ 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, CO₂, 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 CO₂ 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 CO₂ 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 CO₂ concentration is actually increasing slowly; however, it is easier to calculate what might happen if a large increase in the CO₂ 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 CO₂ 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 CO₂ 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 CO₂-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 CO₂ 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 result-

ing from increases in the CO₂ 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 CO₂ 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 CO₂ concentration. Time-dependent climate model calculations using standard scenarios of fossil fuel CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentration.

CLIMATIC EFFECTS OF OTHER PERTURBING FACTORS

The ongoing increase in the CO₂ 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 multi-millennia 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 CO₂ 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 CO₂ 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 CO₂ concentration.

Many gases being injected into the atmosphere as a result of various societal activities can act like CO₂ to trap outgoing infrared radiation and to warm the climate. For example, CH₄ 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 CFCl₃ and CF₂Cl₂, 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 N₂O, CH₄, CFCl₃, and CF₂Cl₂ and their induced changes in O₃ from climate-chemistry interactions could be as large as those estimated from the expected increase in the CO₂ 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 CO₂ 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 CO₂ 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 CO₂-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 CO₂-induced warming.

SUMMARY OF CLIMATE PROJECTION STUDIES

The atmospheric CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 (CO₂) 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 CO₂-induced climate changes be obtained as soon as possible. The strategy for detecting CO₂-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 CO₂ concentration, that is, the "CO₂-signal."

The climate research community has devoted a great deal of attention to the problem of isolating and detecting the CO₂-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 CO₂ concentration.

The objective of this volume of the State-of-the-Art series is to document what is known about detecting the CO₂-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 CO₂-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 CO₂-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 CO₂ 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 CO₂-induced changes must be sought in data sets that may actually include some early climatic effects, probably relatively small, of rising CO₂ 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 CO₂ concentration, although the magnitude of the changes will depend distinctively on the concentration of each species. Consequently, identification and isolation of the CO₂-induced climate changes from those resulting from other causes are difficult tasks.

THE RADIATIVE SIGNAL OF INCREASING CARBON DIOXIDE

The direct effect of changing CO₂ 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 CO₂-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 CO₂ 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 CO₂, water vapor (H₂O), ozone (O₃), and other trace gases, primarily nitrous oxide (N₂O), methane (CH₄), and the chlorocarbons (e.g., CFC₁₅ and CF₂Cl₂). 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 CO₂-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 CO₂ 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 CO₂ 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 CO₂-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 CO₂ and trace gas concentrations increase. A major source of uncertainty is the lack of understanding about the radiative properties of atmospheric gases, particularly the H₂O 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentration. Statistical attribution is made difficult by the natural variability of the climate, which acts as a noise against which the CO₂, or CO₂ plus trace gas, signal must be detected. In choosing a climatic variable or parameter to monitor for detecting CO₂ 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 CO₂ concentration since the middle of the 19th century should already have caused an appreciable global surface warming. The amount of the CO₂ warming estimated to have occurred depends on (1) the preindustrial CO₂ concentration, (2) the size of the model-predicted equilibrium temperature increase for a doubling of the CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentration, which span the range from about 1.5 to 4.5°C.

If more precise values were known for the preindustrial CO₂ concentration and the lag effect of the oceans, a sharper evaluation of climate model results would be possible. For example, if the CO₂ 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 CO₂ concentration, unequivocal identification of a CO₂ 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 CO₂ concentration is in explaining the decadal and longer time scale fluctuations in the temperature record, particularly the cooling of Northern Hemisphere land areas that occurred from about 1940 to 1970. Until these medium time scale fluctuations have been adequately explained or overtaken by further warming, claims regarding detection of CO₂ 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 CO₂ concentration and as confirmatory evidence of CO₂-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 CO₂ 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 CO₂-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 CO₂-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 CO₂-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 CO₂-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 stud-

ies and the modeling of climate-cryosphere (snow and ice) interactions. For example, estimates of the expected CO₂-induced changes of snow cover are currently made by simple interpolation between equilibrium climate states having one and two times the present CO₂ 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 CO₂-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 CO₂ 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 CO₂-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 CO₂ concentration are not yet evident, although changes that have occurred are not inconsistent with CO₂ 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 CO₂ 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 CO₂ 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 CO₂-induced signal.

Because CO₂-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 CO₂ effects and that, on the regional scale, could well be as important as potential CO₂-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 CO₂-induced signal in this record extremely difficult.

When averaged over subcontinental to continental scales, projected CO₂-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 CO₂ 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 CO₂ 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 CO₂-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 CO₂ effect, aspects of these different analyses are not consistent with each other and the derived CO₂ effect is somewhat smaller than suggested by recent climate modeling studies.

Several factors make it impossible to predict precisely when the CO₂-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 CO₂ and trace gas concentrations. If CO₂ 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 CO₂ signal should become much more evident over the next few decades.

TASKS FOR THE FUTURE

The overall goal of the CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂-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 CO₂ 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 CO₂ 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 CO₂-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 CO₂-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 (CO₂) is an essential compound for life on this planet. Understanding the direct effects of increasing atmospheric CO₂ concentration on vegetation is an issue independent of all other global CO₂ effects. Plants absorb CO₂ from the atmosphere and become the food supply for other organisms. Because plant growth is limited by the amount of CO₂ in the atmosphere, it is critical to understand how the world's vegetation will respond as the CO₂ 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 CO₂ almost certainly was a limiting factor in agricultural productivity and ecological interrelationships. As agricultural technology has been increasing yields throughout this century, atmospheric CO₂ 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 CO₂. Thus, it is possible that some fraction of the increased agricultural yield that has occurred in this century is due to increased atmospheric CO₂ concentration.

Research has shown, however, that not all species respond to CO₂ in the same manner or magnitude. Plants with high conductance for the diffusion of CO₂ will have greater growth than plants with lower CO₂ conductance. Because many agricultural weeds have high conductance, they could have a comparatively larger growth response to increased CO₂ 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 CO₂ increases. For example, soybean leaves became carbon rich and nitrogen poor as atmospheric CO₂ 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 CO₂ enrichment is needed for future agricultural productivity to be engineered wisely.

In nonagricultural ecosystems, the direct effects of increasing atmospheric CO₂ 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 CO₂ 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 CO₂. However, a number of secondary responses may occur in conjunction with an increased rate of CO₂ 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 CO₂ on vegetation and the subsequent effects on ecosystems. The indirect effects on plants that might occur from a CO₂-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 CO₂ 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 CO₂ on vegetation has been underway for more than 50 years. Horticulturists realized years ago that adding CO₂ to the air in greenhouses would enhance plant growth. Many commercial greenhouses are routinely CO₂ enriched to accelerate plant development and increase economic yield, and the use of CO₂-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 CO₂ and other factors: the control and monitoring of temperature, light intensity, relative humidity, air flow, and water and nutrient status of the soil. Although CO₂ control was sometimes employed, sufficient light intensity and routine CO₂ enrichment were not generally available for adequate CO₂ experiments until the late 1970s. Therefore, much of the early data on plant responses to CO₂ 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 CO₂ to determine CO₂ responses. Leaf chambers have great potential for basic research on individual plant physiology and biochemistry. The major weaknesses of this approach are that only part of the plant is CO₂ enriched and that short-term measurements do not adequately describe plant responses associated with anatomical or morphological characteristics that may be CO₂ 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, CO₂, 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 CO₂ response. Both phytotrons and improved plant growth chambers have produced much of the dependable information now available on plant responses to long-term CO₂ enrichment. Only one of the phytotrons in the United States is being used now in CO₂ 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 CO₂ 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 CO₂ levels. They are essentially plastic enclosures placed around field crops. Air is drawn into a box by fan, enriched with CO₂, 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 CO₂, temperature, and humidity is not as good as in closed chambers.

The CO₂ enrichment of an uncontained space in a field or ecosystem may be attempted with a free-air-CO₂-enrichment (FACE) facility. In this approach, the CO₂ 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 CO₂. 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 CO₂ 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 CO₂ effects.

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

Improve lighting and CO₂ control in controlled environment growth chambers to be used for CO₂ enrichment research.

Increase the use of existing phytotron facilities for CO₂ 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-CO₂-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 CO₂; and to evaluate interactions such as direct effects of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ on vegetation include the following:

Develop semimechanistic CIP models of ecosystems and cropping systems that contain those CO₂ 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 CO₂ concentration and other environmental factors that affect plant growth. For example, as CO₂ 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 CO₂ fixed to water vapor lost is termed water-use efficiency. This is one of the most important potential direct effects of increased levels of CO₂ 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 CO₂ 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 CO₂-enriched atmosphere. Measurements of plants grown for only short periods in high CO₂ environments must be used with great caution. Measurements of CO₂ 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 CO₂ 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 CO₂-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 CO₂ enhancement.

For native annuals, initial growth rate may increase but final weight and size may not be affected by increased CO₂. 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ continues to increase in the future, those species most responsive to the CO₂ 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 CO₂, 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 CO₂ 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 CO₂ enrichment might affect the Earth's global carbon budget. In this context, the effects of CO₂ enrichment may be expressed in terms of changes of net ecosystem production,

$$\text{NEP} = \text{GPP} - (\text{R}_A + \text{R}_H),$$

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 CO₂ 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 CO₂ on autotrophic and heterotrophic respiration must be determined.

The interaction of increasing CO₂ 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 CO₂ enrichment. The " β factor" generally represents a fractional change in NEP in relation to a fractional change in atmospheric CO₂ concentration. Different " β factors" derived have been (1) assumed to be logarithmically proportional to the atmospheric CO₂ 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 CO₂ enrichment. The changing amplitude of the annual atmospheric CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ increase, the following recommendations are made:

Screen for overall growth and yield response under high CO₂ 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-CO₂ 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 CO₂ 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 CO₂ may be affected by light intensity and temperature.

Determine how soil nutrient status affects CO₂ response. More information is also needed about the effects of CO₂ 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 CO₂ 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 CO₂ and also to predicted climate changes.

Determine whether plants grown at high CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ and partial stomatal closure on internal plant water status. To what extent can high CO₂ levels ameliorate plant water stress and maintain high productivity under dry conditions? Similarly, to what extent can high CO₂ 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-CO₂ 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 CO₂ 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 CO₂ 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 (CO₂) question as the scientific foundation for evaluating future energy policy issues. Efforts toward this goal include research on (1) carbon cycle (CO₂ exchange between the world and its atmosphere), (2) the potential for climate change resulting from increased CO₂, (3) the extent of vegetation response to increased CO₂, 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 CO₂. 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 CO₂. Because of these uncertainties, it is currently not feasible to do an impact assessment of the indirect effects of CO₂. 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 CO₂ RESEARCH PROGRAMS

Carbon Cycle

The extent and rate of climate change and vegetation response will depend on the extent and rate of CO₂ change in the atmosphere. Thus, information on the carbon cycle is basic to determining all other effects of CO₂. Among the topics studied, agriculture, forests, and fisheries appear to have the potential to be affected directly by CO₂. The direct response of agriculture and forests to CO₂ is being studied separately in the vegetation response research program. The concentration of dissolved CO₂ in sea water, which will be in equilibrium with CO₂ 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 CO₂ 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 CO₂. These currently preclude prediction, over long periods of time, of the rate of increase and the eventual maximum concentration of atmospheric CO₂.

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 km²; (2) some specialty crops are grown in small regions, whereas major grain belts cover thousands of km²; 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 CO₂-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 CO₂ from the atmosphere, and increased CO₂ 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 CO₂, 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 CO₂ 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 CO₂-induced vegetation response of important crop, forest, native, and aquatic plant species is currently uncertain, as are the interactive effects of CO₂-induced climate change and vegetation response on vegetation.

RESEARCH NEEDS WITHIN THE TOPICS STUDIED

In addition to the information needed from CO₂ 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 CO₂-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 CO₂-induced effects. The cost of such items as irrigation, fertilizer, and pest control and the economic return from particular crops will interact with CO₂-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 CO₂) on ocean chemistry; and (5) assessing the effects of dissolved CO₂ on primary productivity.

National and international regulations of fishery catches may interact with CO₂-induced effects; that is, should there be a combination of overfishing and detrimental CO₂-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 CO₂-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 CO₂ 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 CO₂-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 CO₂-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 CO₂ 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 CO₂, (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 CO₂. 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 CO₂ (either beneficially or detrimentally), is uncertain.

DATA NEEDS AND TASKS FOR THE FUTURE

There are many uncertainties about the indirect effects of increased CO₂. To clarify most of these, reliable information about the direct effects of CO₂ 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 CO₂ 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 CO₂-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 CO₂, 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 CO₂.
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 CO₂-INDUCED CLIMATIC CHANGE

The rising concentration of CO₂ 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 CO₂-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 $0.6 \pm 0.3^\circ\text{C}$ 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	$+0.5 \pm 0.3$	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

^aNote: 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 numer-

ical 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 CO₂, 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 CO₂-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 CO₂ 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 CO₂-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 CO₂ 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 beneath 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 CO₂-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 CO₂ 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 CO₂-Enhanced Environment^a

Ice Mass	Annual Probable Contribution to Sea Level with Steady-State 2 × 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

^aFor 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.

^bValues 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 CO₂-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 CO₂-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 CO₂ 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 10² 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 CO₂ (pCO₂) exerted by seawater to the fractional change in total CO₂ dissolved in the ocean waters. The buffer factor relates the partial pressure of CO₂ in the ocean to the total ocean CO₂ concentration at constant temperature, alkalinity and salinity. The Revelle factor is a useful parameter for examining the distribution of CO₂ between the atmosphere and the ocean, and determines in part the amount of CO₂ 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 CO₂. [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 CO₂ enrichment that could occur in natural or agricultural systems as a result of an increase in the atmospheric concentration of CO₂. [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 tem-

peratures, 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]

CO₂ reference gas—A mixture of a known quantity of CO₂-in-air or CO₂-in-N₂ 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 CO₂ to the atmosphere. Regional and global impacts may result from the release of CO₂ 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 counter-clockwise 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 tri-atomic 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 transferred 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]

pCO₂—The partial pressure of CO₂ in the atmosphere and the ocean. In the atmosphere, the partial pressure of CO₂ is defined as the pressure the CO₂ 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 CO₂ in the atmosphere is determined by the atmospheric CO₂ concentration and atmospheric temperature. In the ocean the pCO₂ is determined by the amount of dissolved CO₂ and H₂CO₃. It varies with total CO₂, alkalinity, latitude, depth, and temperature. Biological processes in the ocean also exert an influence on the pCO₂ 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: ¹⁸O, in ice sheets, ¹⁸O, ²H, and ¹³C in tree rings; CaCO₃ 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 hydro-spheric 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 $^{14}\text{C}/\text{C}$ or $^{13}\text{C}/\text{C}$ 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 $^{14}\text{C}/\text{C}$ 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 quantita-

tive 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 com-

monly 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 CO₂ 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 CO₂ uptake as well as water loss, thus decreasing the photosynthetic rate. However, under conditions of elevated CO₂ concentration, the CO₂ gradient between the atmosphere and the leaf is higher than under ambient conditions, and CO₂ can pass through partially closed stomates at a rate similar to that of low CO₂ and open stomates. The humidity gradient remains the same at high CO₂, 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 CO₂ 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 CO₂ Research

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

Table 3. Common Conversion Factors

Area-length-volume

1 acre = 43,560 ft² = 4,047 m²

1 acre-foot = 1.2335×10^3 m³

1 cubic foot (ft³) = 0.02832 m³

1 hectare (ha) = 10,000 m² = 2.47 acres

1 square mile (mi) = 2.59×10^6 m²

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/km³

1 ppm by volume of atmosphere CO₂ = 2.130 Gt C

12.011 g C = 1 mole CO₂

1 g C = 3.667 g CO₂

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^{-1}
1 kcal =	4184	3966×10^{-10}	1	142.9×10^{-9}	683.8×10^{-9}	93.47×10^{-9}	112.3×10^{-6}	132.7×10^{-10}
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, m³ 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 CO₂ Emissions

Using Global Fuel Production Data

$$[\text{CO}_2_i = (\text{P}_i)(\text{FO}_i)(\text{C}_i)]^*$$

From Coal Production

CO_2_i = CO₂ emissions in 10⁶ tons C

P_i = Annual production in 10⁶ tons coal equivalent ($\pm \approx 11.2\%$)

FO_i = Effective fraction oxidized in year of production = $0.982 \pm 2\%$

C_i = Carbon content in tons C per ton coal equivalent = $0.746^* \pm 2\%$

From Natural Gas Production

CO_2_i = CO₂ emissions in 10⁶ tons C

P_g = Annual production in thousands of 10¹² joules ($\pm \approx 10\%$)

FO_g = Effective fraction oxidized in year of production = $0.98 \pm 1\%$

C_g = Carbon content in 10⁶ tons per thousand 10¹² joules = $0.0137 \pm 2\%$

From Natural Gas Flaring

CO_2_i = CO₂ emissions in 10⁶ tons C

P_f = Annual gas flaring in 10⁶ cubic meters ($\pm \approx 20\%$)

FO_f = Effective fraction oxidized in year of flaring = $1.00 \pm 1\%$

C_f = Carbon content in tons per thousand cubic meters = $0.525 \pm 3\%$

From Crude Oil and Natural Gas Liquids Production

CO_2_i = CO₂ emissions in 10⁶ tons C

P_l = Annual production in 10⁶ tons ($\pm \approx 8\%$)

FO_l = Effective fraction oxidized in year of production = $0.918 \pm 3\%$

C_l = Carbon content in tons C per ton crude oil = $0.85 \pm 1\%$

*All masses are in metric tons (10³ 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 Environmental 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
CIC	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
LOF	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, Antarctica

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 CO₂ 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	<i>Theragra chalcogramma</i>	Flatfish	<i>Pseudopleuronectes americanus</i>
Alfalfa weevil	<i>Phytonomus posticus</i>	Foxtail	<i>Setaria</i> spp.
Alfalfa	<i>Medicago sativa</i>	Fur seal	<i>Callorhinus</i> spp.; <i>Arctocephalus</i> spp.
American plane tree	<i>Platanus occidentalis</i>	Giant ragweed	<i>Ambrosia trifida</i>
Anchovy	<i>Anchoa</i> spp.	Grape	<i>Vitus</i> spp.
Ash	<i>Fraxinus</i> spp.	Herring	<i>Clupea harengus</i>
Aspen	<i>Populus grandidentata</i>	Hickory	<i>Carya</i> spp.
Atlantic cod	<i>Gadus morhua</i>	Hookworm	<i>Ancyllostoma</i> spp.; <i>Necator</i> spp.
Atlantic herring	<i>Clupea harengus harengus</i>	Hydrilla	<i>Hydrocharitaceae</i> spp.
Barley	<i>Hordeum vulgare</i>	Itch grass	<i>Roltboellia exaltata</i>
Barnyard grass	<i>Echinochloa crus-galli</i>	Jack pine	<i>Pinus banksiana</i>
Beggar's lice	<i>Desmodium paniculatum</i>	Jimson weed	<i>Datura stramonium</i>
Black cutworm moth	<i>Argotis ypsilon</i>	Kale	<i>Brasica oleracea</i>
Blueberry	<i>Vaccinium uliginosum; Vaccinium</i> <i>vitis-idaea</i>	Kittiwake	<i>Rissa</i> spp.
Bluegrass	<i>Poa</i> spp.	Knobcone pine	<i>Pinus attenuata</i>
Brahman cattle	<i>Bos indicus</i>	Lamb's-quarter	<i>Chenopodium album</i>
Bristlecone pine	<i>Pinus longaeva</i>	Lettuce	<i>Lactuca sativa</i>
California bristlecone pine	<i>Pinus aristata</i>	Limber pine	<i>Pinus flexilis</i>
California halibut	<i>Paralichthys californicus</i>	Loblolly pine	<i>Pinus taeda</i>
Canary grass	<i>Phalaris</i> spp.	Lucern	<i>Medicago sativa</i>
Capelin	<i>Mallotus villosus</i>	Maize	<i>Zea mays</i>
Catfish	<i>Ictalurus</i> spp.	Marsh tea	<i>Ledum palustre</i>
Cattle	<i>Bos taurus</i>	Millet	<i>Setaria</i> spp.
Chlorella	<i>Chlorella vulgaris</i>	Oak	<i>Quercus</i> spp.
Chrysanthemum	<i>Chrysanthemum</i> spp.	Oats	<i>Avena</i> spp.
Clover	<i>Trifolium</i> spp.	Okra	<i>Hibiscus esculentus</i>
Common murre	<i>Uria aalge</i>	Oleander	<i>Nerium oleander</i>
Corn borer	<i>Pyrausta nubilaris</i>	Oysters	<i>Ostrea</i> spp.
Corn	<i>Zea mays</i>	Pacific cod	<i>Gadus macrocephalus</i>
Cotton grass	<i>Eriophorum vaginatum</i>	Pacific hake	<i>Merluccius productus</i>
Cotton	<i>Gossypium</i> spp.	Pacific herring	<i>Clupea harengus pallasi</i>
Cottonwood	<i>Populus deltoides</i>	Peanut	<i>Arachis hypogaea</i>
Coulter pine	<i>Pinus coulteri</i>	Peas	<i>Pisum</i> spp.
Creosote bush	<i>Larrea divaricata</i>	Pennsylvania knotweed	<i>Polygonum pensylvanicum</i>
Cucumber	<i>Cucumis sativa</i>	Pensacola Bahia grass	<i>Paspalum notatum</i>
Dalis grass	<i>Paspalum dilatatum</i>	Perennial rye grass	<i>Lolium perenne</i>
Darnel rye grass	<i>Lolium tremulatum</i>	Peruvian anchovy	<i>Engraulis ringens</i>
Dungeness crab	<i>Cancer magister</i>	Phlox	<i>Phlox drummondii</i>
Dwarf arctic birch	<i>Betula nana</i>	Pigweed	<i>Amaranthus retroflexus</i>
Eastern poplar	<i>Populus deltoides</i>	Pineapple	<i>Ananas cosmosus</i>
Faba bean	<i>Vicia faba</i>	Pink shrimp	<i>Pandalus borealis</i>
Festuca	<i>Festuca elatior</i>	Pinto bean	<i>Phaseolus</i> spp.
		Plaice	<i>Pleuronectes platessa</i>

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

INDEX OF SCIENTIFIC NAMES

This Glossary gives the common names associated with the scientific names of flora and fauna mentioned in the six CO₂ reports. In some cases, more than one common name is associated with a single scientific name and vice versa.

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

<i>Pandalus borealis</i>	Pink shrimp	<i>Rissa</i> spp.	Kittiwake
<i>Paralichthys californicus</i>	California halibut	<i>Roccus saxatilis</i>	Striped bass
<i>Paspalum dilatatum</i>	Dalis grass	<i>Rolboellia exaltata</i>	Itch grass
<i>Paspalum notatum</i>	Pensacola Bahia grass	<i>Rosa</i> spp.	Rose
<i>Phalaris</i> spp.	Canary grass	<i>Sacchanum officinarum</i>	Sugarcane
<i>Phaseolus</i> spp.	Pinto bean	<i>Saxifraga flagellaris</i>	Saxifrage
<i>Phlox drummondii</i>	Phlox	<i>Setaria</i> spp.	Millet, foxtail
<i>Physter catodon</i>	Sperm whale	<i>Solanum tuberosum</i>	White potato
<i>Phytonomus posticus</i>	Alfalfa weevil	<i>Sorghum bicolor</i>	Sorghum
<i>Pinus aristata</i>	California bristlecone pine	<i>Sorghum halapense</i>	Sorghum
<i>Pinus attenuata</i>	Knobcone pine	<i>Sorghum sudanese</i>	Sorghum
<i>Pinus banksiana</i>	Jack pine	<i>Spirulina platensis</i>	Spirulina
<i>Pinus coulteri</i>	Coulter pine	<i>Squalus acanthias</i>	Spiny dogfish
<i>Pinus flexilis</i>	Limber pine	<i>Stylosanthus humilis</i>	No common name
<i>Pinus longaeva</i>	Bristlecone pine	<i>Sus scrofa</i>	Swine
<i>Pinus ponderosa</i>	Ponderosa pine	<i>Termes</i> spp.	Termite
<i>Pinus taeda</i>	Loblolly pine	<i>Thalarctos maritimus</i>	Polar bear
<i>Pisum</i> spp.	Peas	<i>Theragra chalcogramma</i>	Alaska pollack
<i>Platanus occidentalis</i>	American plane tree	<i>Thunnus saliens</i>	Tuna
<i>Pleuronectes platessa</i>	Plaice	<i>Tidestromia oblongifolia</i>	No common name
<i>Poa</i> spp.	Bluegrass	<i>Tobascum nicotinana</i>	Tobacco
<i>Polygonum pensylvanicum</i>	Pennsylvania knotweed	<i>Trifolium repens</i>	White clover
<i>Populus deltoides</i>	Cottonwood	<i>Trifolium</i> spp.	Clover
<i>Populus deltoides</i>	Eastern poplar	<i>Triticum aestivum</i>	Wheat
<i>Populus grandidentata</i>	Aspen	<i>Uria aalge</i>	Common murre
<i>Populus</i> spp.	Poplar	<i>Vaccinium uliginosum</i>	Blueberry
<i>Pseudopleuronectes americanus</i>	Flatfish	<i>Vaccinium vitis-idaea</i>	Blueberry
<i>Puffini</i> spp.	Shearwater	<i>Vicia faba</i>	Faba bean
<i>Pyrausta nubilaris</i>	Corn borer	<i>Vitus</i> spp.	Grape
<i>Quercus rubra</i>	Red oak	<i>Zalophus</i> spp.	Sea lion
<i>Quercus</i> spp.	Oak	<i>Zea mays</i>	Corn, maize
<i>Raphanus</i> 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 CO₂ Effects: Water Resources, Agriculture, Fisheries, Forests, and Human Health*; and **GLA**: *Glaciers, Ice Sheets, and Sea Level: Effect of a CO₂-Induced Climatic Change*.

17th International Horticultural Congress, **DIR**: 3

Aagaard, K., **PRO**: 126

Abbott, C. G., **PRO**: 42

Abelson, P., **INF**: 170

Aber, J. D., **DIR**: 139; **DET**: 158

Achutuni, R., **DET**: 77

Ackerman, S. H., **INF**: 38, 199, 200

Ackerman, T. P., **INF**: 44, 46

Ackley, S. F., **PRO**: 112, 113, 124, 125

Acock, B., **DIR**: 19, 41, 44, 46, 64, 65, 69, 73, 78, 80, 101, 130, 140

Adams, J. A., **GCC**: 120

Adams, W. P., **PRO**: 116; **GLA**: 147

Addy, N. D., **GCC**: 199

Adie, R. J., **GLA**: 46

Afanas'eva, V. B., **PRO**: 120, 121

Agrios, G. N., **DET**: 84

Aguilar, M. I., **DIR**: 70, 71, 265

Aharon, P., **GCC**: 180

Ahlmann, H. W., **GLA**: 217

Aikman, J. M., **DET**: 151

Ajtay, G. L., **GCC**: 115, 116, 117, 119, 121, 123, 125, 132, 180

Akagawa, M., **PRO**: 126

Akers, T. G., **DET**: 190

Akita, S., **DIR**: 5, 112, 221, 222, 224, 227, 237, 238, 241, 251, 263, 269

Albert, D. G., **GLA**: 178

Albritton, D. J., **DIR**: 75

Aldridge, B. N., **DET**: 52

Aleksandrov, V. V., **INF**: 211, 212, 346

Alexander, R. C., **INF**: 116, 120

Alheit, M. M., **GLA**: 74

Allen, E. L., **GCC**: 217, 232

Allen, J. C., **DIR**: 39

Allen, L. H., Jr., **DIR**: 3, 14, 23, 24, 25, 27, 60, 61, 65, 68, 69, 70, 78, 79, 174, 175, 189

Allen, W. T. R., **PRO**: 130

Allison, I. F., **GLA**: 172, 233

Allison, I., **PRO**: 124

Almgren, T., **GCC**: 86

Alpert, J. C., **INF**: 211

Alt, B. T., **GLA**: 152

Alton, M. S., **DET**: 124

Altshuller, A., **INF**: 200

Alvarez, L. W., **INF**: 168

Alvarez, W., **GCC**: 195, 200, 205

Ambach, W., **PRO**: 135; **GLA**: 43, 156, 160, 256, 257, 259, 260, 261

Ambe, Y., **PRO**: 159

American Association for the Advancement of Science, **DET**: 4

American Society for Testing Materials, **GCC**: 73

American Society of Civil Engineers, **DET**: 45

Amiel, A. J., **GCC**: 122

Amos, A. F., **GLA**: 117

Anderson, A. S., **DIR**: 130

Anderson, D. L., **GCC**: 194

Anderson, H. S., **DET**: 44

Anderson, M. R., **PRO**: 124; **GLA**: 241

Anderson, P. J., **DET**: 109

Anderson, R. M., **DET**: 194

Anderson, T. W., **DET**: 179, 181

Andre, M., **DIR**: 263

Andreasen, J. O., **GLA**: 168

Andrews, D. F., **GLA**: 86

Andrews, J. T., **PRO**: 131; **INF**: 247

Andrews, M., **INF**: 247

Angell, J. K., **GCC**: 49, 50; **PRO**: 67, 69, 70, 71, 73, 75, 76, 156 **INF**: 202, 216, 218

Anisimov, A. A., **DIR**: 113

Aoki, M., **DIR**: 57, 58, 160

Apasova, E. G., **PRO**: 156, 159

Apel, P., **DIR**: 270

Arakawa, A., **INF**: 113

Arctowski, H., **PRO**: 42

Aristarain, A., **GLA**: 207

Arkin, G. F., **DIR**: 44

Arking, A., **INF**: 33, 34, 37

Armentano, T., **DIR**: 3, 4

Armentano, T. V., **GCC**: 117, 119, 120, 121, 122, 125, 126, 129, 130, 197, 202, 255, 267

Armstrong, C., **DET**: 192

Arnold, K. C., **GLA**: 149, 150

Arons, A. B., **GCC**: 169

Arpe, K., **PRO**: 68

Arthur, M. A., **GCC**: 195

Aston, A. R., **DIR**: 197, 198; **DET**: 35

Ajtay, G. L., **DIR**: 176, 181

Atmospheric Environment Service, Canada, **PRO**: 118, 119

Atwater, M. A., **INF**: 46

Aubin, E., **GCC**: 37

Aubrey, D. G., **GLA**: 75, 76, 78, 80

Augustsson, T., **INF**: 41, 42, 87, 153, 240, 292, 299, 302, 305, 346

Austin, H. B., **DET**: 100, 110, 113

Ausubel, J. H., **GCC**: 217, 239, 241; **DET**: 6

Aweto, A. O., **GCC**: 122
 Ayers, J. P., **INF**: 201
 Azevedo, A. E. G., **GCC**: 91, 93, 146, 165, 166, 167, 168
 Bacastow, R. B., **GCC**: 38, 47, 48, 49, 50, 87, 98, 99, 100, 102, 130, 144, 147, 148, 153, 154, 155, 158, 159, 217, 218, 222, 231, 240, 250, 268, 269, 272, 273, 280; **DIR**: 42, 174, 177, 178, 179; **DET**: 11
 Bach, W. A., **GCC**: 278, 279, 280; **INF**: 199, 203, 204
 Bachelet, D., **DIR**: 44
 Backus, G., **PRO**: 153
 Badger, M. R., **DIR**: 113, 120, 122
 Baerreis, D. A., **INF**: 200
 Baes, C. F., Jr., **GCC**: 7, 87, 101, 102, 103, 143, 180, 191, 192, 202, 263; **DET**: 100
 Bailey, K. M., **DET**: 108, 109, 111, 113, 127, 137
 Bainton, D., **DET**: 179
 Bakayev, U. G., **GLA**: 173
 Baker, D. G., **PRO**: 34
 Baker, D. N., **DIR**: 3, 14, 19, 44, 59, 60, 61, 71, 129, 230
 Baker, V. R., **DET**: 30
 Baker-Blocker, A., **DET**: 181
 Bakun, A., **DET**: 100, 133, 137
 Baldwin, B., **INF**: 199
 Bandy, A. R., **INF**: 198
 Barber, D. A., **DIR**: 133
 Barber, R. T., **GCC**: 50; **DET**: 127
 Bardin, V. I., **GLA**: 172, 204
 Barfield, B. J., **DET**: 82
 Barnard, J. C., **GCC**: 30, 37
 Barnes, P., **GLA**: 52
 Barnett, J. J., **PRO**: 25
 Barnett, T. P., **PRO**: 32, 39, 40, 58, 62, 65, 94, 95, 97, 99, 100, 102, 103, 153; **GLA**: 13, 74, 75, 76, 86, 93, 95, 104
 Barney, G. O., **GCC**: 123, 124
 Barnhardt, E. A., **INF**: 201
 Barnola, J. M., **GCC**: 28, 29, 35, 37
 Barrie, L. A., **INF**: 201
 Barron, E. J., **GCC**: 34, 179, 195, 300; **INF**: 240
 Barry, R. G., **PRO**: 111, 115, 118, 120, 122, 123, 124, 127, 129, 134; **GLA**: 43, 241, 242, 243, 245, 261
 Bartlein, P. J., **DET**: 158; **INF**: 247, 248, 249, 250, 251
 Baseline 1979, **GCC**: 45
 Baseline 1981, **GCC**: 45
 Bassett, J. R., **DET**: 150
 Batchelder, R. B., **GCC**: 177
 Bates, G. T., **INF**: 108
 Batschelet, E., **DIR**: 39
 Bauer, A., **GLA**: 27, 155, 156, 161, 162, 164
 Bauer, E., **INF**: 197, 219
 Bauer, R., **INF**: 349
 Baumol, W. J., **DET**: 38
 Bazilevich, N. I., **GCC**: 181
 Bazzaz, F. A., **DIR**: 6, 13, 19, 61, 75, 112, 119, 121, 127, 129, 131, 134, 139, 140, 141, 157, 158, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 182, 188, 190, 195, 199, 223, 224, 228, 246, 251, 257
 Beardsmore, D. J., **GCC**: 44, 54, 254, 268
 Beck, S. M., **DIR**: 132
 Becker, E. B., **GLA**: 293
 Becker, S., **DET**: 177
 Beets, J. L., **DET**: 179, 180, 181
 Behrendt, J. C., **GLA**: 306
 Belacy, N., **GCC**: 20, 29, 37, 159, 161, 251, 252, 267, 270, 272
 Bell, E. E., **PRO**: 25
 Bell, F. H., **DET**: 110
 Bell, P. R., **GCC**: 182; **INF**: 195
 Bellamy, D. T., **GCC**: 197
 Belmont, A. D., **INF**: 202
 Benci, J. F., **DET**: 4
 Benjamin, S. G., **INF**: 201
 Benson, C. S., **GLA**: 8, 26, 256, 260, 261
 Benson, M. A., **DET**: 30
 Bentley, C. R., **PRO**: 133, 134, 135, 136; **GLA**: 31, 121, 172, 178, 179, 181, 182, 183, 186, 188, 280, 317, 318, 319, 320, 325, 326
 Berger, A., **PRO**: 6
 Berger, A. L., **INF**: 16, 66, 246
 Berger, W. H., **GCC**: 33, 192
 Berghósson, P., **PRO**: 64
 Bermudez, A., **DIR**: 147
 Bernadini, O., **GCC**: 218, 229, 235
 Bernard, R. P., **DET**: 177
 Berner, R. A., **GCC**: 31, 97, 192, 193, 194, 195, 196, 198, 203, 300; **INF**: 240
 Berner, W., **GCC**: 32, 179
 Berry, M. O., **PRO**: 118
 Betin, V. V., **PRO**: 122
 Betzer, P. R., **GCC**: 296
 Bevertton, R. J. H., **DET**: 109
 Bhalme, H., **PRO**: 156
 Bhangoo, M. S., **DIR**: 75
 Bhanu Kumar, O. A. R. U., **PRO**: 121
 Bhattacharya, N. C., **DIR**: 67, 70, 130, 261, 262
 Bidwell, R. G. S., **DET**: 75
 Bierhuizen, J. F., **DIR**: 56, 230
 Bigelow, F. H., **PRO**: 34
 Bigg, E. K., **INF**: 200
 Biggs, D. C., **GLA**: 117
 Bilello, M. A., **PRO**: 127
 Billen, G., **GCC**: 96
 Billewicz, W. L., **DET**: 177
 Billings, S. M., **DIR**: 131, 132
 Billings, W. D., **GCC**: 130, 131, 133; **DIR**: 5, 131, 132, 137, 138, 139, 148
 Bindschadler, R. A., **PRO**: 128; **GLA**: 50, 220, 326
 Bingham, G. E., **DIR**: 6, 17
 Birchfield, G. E., **PRO**: 114, 115; **GLA**: 224
 Birsoy, Y. K., **PRO**: 152
 Bischoff, W., **GCC**: 44
 Biscoe, P. V., **GCC**: 119; **DIR**: 39, 46
 Bishop, J. F., **GLA**: 202, 204, 309
 Björkman, O., **DIR**: 5, 42, 46, 57, 72, 73, 114, 123, 130, 157, 161, 178; **DET**: 28
 Björkström, A., **GCC**: 98, 99, 100, 102, 148, 152, 153, 154, 155, 159, 180, 250, 270, 271, 272, 273; **DIR**: 179
 Björnsson, H., **GLA**: 234
 Blackburn, T., **PRO**: 34
 Blackburn, W. H., **DET**: 44
 Blackman, F. F., **DIR**: 72
 Blackmer, A. M., **INF**: 197
 Blackwelder, W. C., **DET**: 181, 183
 Blake, D., **INF**: 6
 Blake, D. R., **INF**: 194, 195
 Blake-Jacobson, M., **DIR**: 44, 121, 134, 141
 Blanchard, D. C., **DET**: 191; **INF**: 201
 Blanchet, J. P., **INF**: 46
 Bland, M. K., **DET**: 103, 173, 197
 Blanford, H., **PRO**: 156
 Blasing, T. J., **GCC**: 191, 263; **DET**: 78, 80, 153, 173
 Blayo, C., **DET**: 176
 Bliss, L. C., **DIR**: 137, 138
 Bloom, A. J., **DIR**: 17
 Bloom, A. L., **PRO**: 6; **GLA**: 94
 Bode, H. W., **INF**: 284
 Bodhaine, B. A., **GCC**: 38, 41, 42, 44, 48, 50; **INF**: 200
 Boer, G. J., **PRO**: 67, 68
 Boggess, W. R., **DET**: 5, 34, 41, 50, 61
 Boggs, S., Jr., **GLA**: 82
 Bohn, H. L., **GCC**: 117, 122, 181
 Bolin, B., **GCC**: 6, 44, 88, 101, 117, 119, 120, 124, 132, 143, 146, 150, 152, 159, 165, 166, 167, 168; **DIR**: 3, 4, 179
 Bolton, J. A., **INF**: 99
 Bonatti, E., **INF**: 200
 Boote, K. J., **DIR**: 43, 69
 Borchert, J. R., **INF**: 249
 Bormann, F. H., **GCC**: 122, 143, 294; **DET**: 151
 Borowitzka, M. A., **DET**: 100
 Borzenkova, I. I., **PRO**: 57, 58, 59, 61; **INF**: 244
 Botkin, D. B., **GCC**: 132; **DIR**: 176; **DET**: 158, 162
 Boughner, R. E., **INF**: 210
 Boulter, D., **DIR**: 133
 Bouma, D., **DIR**: 113

Bourke, R., PRO: 152
 Boussingault, M., GCC: 177, 205
 Bovallius, A., DET: 191
 Bowes, G., DIR: 58
 Bowes, M. D., DET: 40
 Bowling, S. A., PRO: 120
 Box, E. O., GCC: 119, 186; DIR: 39
 Boyer, J. S., DIR: 113
 Bradbury, J. P., GCC: 266
 Bradley, R. S., PRO: 34, 35, 37, 39, 40, 48, 59, 64, 152; GLA: 149
 Bradshaw, A. L., GCC: 91
 Braithwaite, R. J., GLA: 159, 160, 161, 260
 Bramryd, T., GCC: 255
 Branton, C., DET: 176
 Braslau, N., INF: 46
 Brass, G. W., GCC: 179
 Brasseur, G., INF: 202, 203
 Braun, E. L., DET: 153, 159, 160
 Brazel, A. J., GCC: 262; DIR: 197, 198; DET: 35; PRO: 151, 160
 Breen, P. J., DIR: 58
 Breitenbeck, G. A., INF: 197
 Bremner, J. M., INF: 197
 Bresler, E., DET: 45
 Brewer, A. W., INF: 198
 Brewer, G., GCC: 266
 Brewer, P. G., GCC: 10, 30, 36, 37, 84, 86, 90, 92, 94, 95, 102, 152, 257, 258, 273; PRO: 102; GLA: 116, 129
 Brewer, P. J., DET: 100, 105
 Bridger, C. A., DET: 185, 187, 188
 Briggs, G. E., DIR: 36, 38
 Briggs, P. C., DET: 37
 Brinkmann, W. A. R., PRO: 57, 63, 120
 Broccoli, J., GLA: 220
 Broecker, W. S., GCC: 6, 9, 30, 32, 33, 34, 36, 88, 90, 91, 92, 93, 94, 95, 96, 97, 99, 100, 103, 104, 143, 146, 150, 151, 152, 153, 156, 157, 169, 179, 191, 192, 195, 205, 256, 262, 267, 269, 272, 282; 293, 294, 296, 299; DET: 97, 139; INF: 163, 179, 180, 181, 240; GLA: 10, 270, 271
 Bromwich, D., GLA: 125
 Brooks, R. L., GLA: 235
 Brown, E. B., DET: 4
 Brown, J., PRO: 131
 Brown, L., DET: 34
 Brown, R. H., GCC: 190, 201
 Brown, S., GCC: 19, 115, 116, 117, 121, 124, 126, 127, 128, 131, 257, 267; DIR: 4
 Browning, S. R., INF: 46
 Brownscombe, J. L., PRO: 73
 Bruchhausen, P. M., GLA: 123
 Brun, W. A., DIR: 68, 71, 72, 73, 132, 134, 245, 251, 255, 258, 260
 Brunig, E. F., GCC: 120, 124
 Brunt, D., INF: 299
 Bryan, K., GCC: 84, 104; PRO: 77, 126; INF: 72, 144, 155, 156, 159, 175, 176, 177, 178, 243; GLA: 268
 Bryson, R. A., PRO: 6, 45, 46, 82; INF: 17, 163, 168, 200, 241, 249
 Budd, W. F., PRO: 112, 115, 127, 134, 136; INF: 73; GLA: 52, 172, 173, 174, 175, 211, 214, 222, 319
 Budiansky, S., INF: 200
 Budko, M. I., GCC: 31, 192, 193, 194; PRO: 57, 58, 59, 113, 136; INF: 70, 85, 161, 169, 215, 242, 244, 289, 303, 308, 313
 Buechley, R. W., DET: 185, 187, 188
 Buston, J. L., GLA: 237
 Bull, C., GLA: 172, 210
 Bull, G. M., DET: 177, 178, 181, 183, 184
 Bullister, J. L., GCC: 90, 92, 94, 258
 Bullrich, K., INF: 200
 Bunnell, F. L., GCC: 179
 Bunting, A. A., PRO: 157
 Burch, D. E., INF: 35
 Burges, S. J., DET: 30, 31, 33, 36, 47
 Buringh, P., GCC: 117, 122, 181
 Burke, R. A., Jr., GCC: 179, 188, 203
 Burkitt, D. P., DET: 183
 Burnet, F. M., DET: 193
 Burton, I., DET: 42, 43
 Burwell, C. C., GCC: 71
 Buskirk, E. R., DET: 176
 Butler, G. D., DIR: 140, 192
 Butzer, K. W., INF: 239, 241, 246
 Buxley, B., DIR: 132
 Bykov, V. D., DET: 32
 Cacuci, D. G., INF: 345, 351, 358
 Caldwell, W., DET: 34
 Calkin, P., GLA: 185
 Callaway, J. M., DET: 31, 32, 57, 82, 195
 Callendar, G. S., GCC: 3, 37; PRO: 31, 57; INF: 285, 286, 288
 Callis, L. B., INF: 197, 198, 203, 207, 210
 Calot, G., DET: 176
 Calvert, A., DIR: 70, 71, 130
 Campbell, C. J., DET: 40
 Campbell, D. E., DET: 179, 180, 181
 Cane, M. A., GCC: 191
 Canham, C. D., GCC: 257
 Carbonell, M., GLA: 161
 Carleton, A. M., PRO: 120, 126
 Carlson, J. H., INF: 299
 Carlson, L. D., DET: 177
 Carlson, R. W., DIR: 6, 13, 19, 61, 75, 112, 127, 129, 134, 157, 158, 162, 163, 167, 168, 182, 195, 223, 224, 228, 245, 246, 251, 256, 257
 Carlson, T. N., INF: 38, 200, 201
 Carmack, E. C., GLA: 119, 123
 Carpenter, T., PRO: 156
 Carsey, F. D., PRO: 125
 Carter, D. R., DIR: 161, 162, 163, 167
 Cass, G. R., INF: 200
 Caswell, H., DIR: 41
 Cavalieri, D. J., PRO: 124, 125, 127; GLA: 125, 243
 Cave, G., DIR: 58, 121
 Caverly, R. S., INF: 38
 Cayan, D. R., PRO: 99
 Cech, I., DET: 181
 Cehak, K., DET: 41
 Central Intelligence Agency, PRO: 122
 Centre National d' Etudes Spatiales, PRO: 45
 Cess, R. D., PRO: 113; INF: 46, 47, 49, 50, 154, 158, 164, 167, 170, 201, 208, 211, 212, 213, 215, 299, 302, 324, 325, 326, 333; GLA: 268
 Chahine, N. T., PRO: 40
 Chambers, M. J., GCC: 198
 Chameides, W. L., INF: 208, 210, 223
 Chan, Y.-H., GCC: 120, 162, 181, 266
 Chandler, R. F., GCC: 122, 234
 Chandler, W., GCC: 220, 236, 241, 242, 243
 Chandrasekhar, S., INF: 29
 Chang, J. S., INF: 203, 210, 221
 Changnon, S. A., PRO: 153
 Chapin, F. S., III, DIR: 134
 Chapman, H. W., DIR: 130
 Chappell, J., PRO: 112
 Charles-Edwards, D. A., DIR: 42, 46, 65, 176
 Charlock, T. P., PRO: 16; INF: 47, 87, 212, 292, 302, 311, 312, 313
 Charlson, R. J., INF: 46, 200
 Charney, J. G., DET: 41; PRO: 157; INF: 9, 204, 216
 Chartier, P., DIR: 46
 Chatfield, R., INF: 223
 Chatigny, M. A., DET: 190
 Chavez, F. P., GCC: 50; DET: 127
 Chebotarev, I. I., DET: 45
 Chedin, A., INF: 33
 Chelton, D. B., DET: 109, 127, 137
 Chemical Manufacturers Association, INF: 196, 219
 Chen, A. W., DET: 151
 Chen, C. T. (C.-T. A.), GCC: 5, 30, 36, 90
 Chen, R. S., PRO: 57, 58, 59, 65, 67, 80, 133
 Chervin, M. B., GCC: 97
 Chervin, R. M., INF: 206, 214, 216
 Childs, S. W., DIR: 44
 Chippendale, G. M., DET: 84
 Chmora, S. N., DIR: 263
 Chou, C. C., INF: 194

Chou, M.-D., INF: 33, 34, 37
 Choudari, J. S., DET: 45
 Chýlek, P., INF: 46, 299, 300
 Ciattaglia, L., GCC: 145
 Cicerone, R. J., INF: 194, 209
 Clapp, P., INF: 50
 Clark, J. A., DIR: 59; GLA: 83, 328
 Clark, W. C., GCC: 11, 177, 242, 268;
 DIR: 4; INF: 196, 219, 222, 239
 Clarke, A., DET: 105
 Clarke, A. D., INF: 201
 Clarke, J. F., DET: 128, 187, 196
 Clary, W. P., DET: 40
 Clausen, H. B., GLA: 156, 173, 183, 184,
 185, 198
 Clayton, H. H., PRO: 36
 Clegg, S., PRO: 45
 Clement, P., GLA: 160
 Cleveland, W. S., GCC: 37, 38, 53, 54,
 131; DIR: 180
 CLIMAP Project Members, INF: 241,
 247
 Climate Analysis Center/NMC/WNC/
 NOAA, GCC: 52
 Cloud, P., GCC: 184, 192, 193, 194, 203
 Clough, J. M., DIR: 18, 58, 111, 112,
 130, 245, 247, 251, 253
 Clough, J. W., GLA: 123
 Coakley, J. A., INF: 43, 46, 47, 48, 167,
 211, 212, 215
 Coase, R. H., DET: 37
 Coates, J. F., GCC: 217, 242
 Cochrane, D., DET: 47
 Cock, J. H., DIR: 70, 71, 238, 240, 241,
 242
 Cockshull, K. E., DIR: 67, 71, 72
 Cogger, B. M. G., DET: 99
 Cohen, P., DET: 177, 183
 Colbeck, S. C., PRO: 116
 Collins, N. M., INF: 195
 Collins, W. B., DIR: 235, 238
 Columbo, U., GCC: 218, 229, 235
 Colvill, A. J., GLA: 234
 Colvocoresses, A. P., GLA: 235
 Conrad, V., PRO: 32, 35
 Consolazio, C. F., DET: 195
 Cook, E. L., DET: 187
 Cooley, K. R., DET: 39
 Cooper, C. F., GCC: 266
 Cooper, R. L., DIR: 68, 71, 72, 73, 134,
 245, 251, 255, 258, 260
 Corona, T. J., PRO: 152, 154, 159
 Coughenour, M. B., DIR: 44
 Council for Agricultural Science and
 Technology, DET: 72, 79, 81, 82, 84
 Council on Environmental Quality, DET:
 4
 Countryman, K. A., GLA: 117
 Covey, C., INF: 211, 212
 Covington, W. W., GCC: 122
 Cowgill, U. M., DET: 176, 177
 Cox, S. K., INF: 38, 49
 Coyne, P. I., GCC: 119; DIR: 6, 17
 Crabtree, R. D., GLA: 206
 Craddock, J. M., PRO: 35
 Craig, H., GCC: 99, 100, 147, 169, 177,
 179, 203; INF: 194
 Crane, A. J., GCC: 99, 100, 146, 148,
 149; INF: 323
 Crane, R. G., PRO: 111, 113, 118, 128
 Crary, A. P., GLA: 186
 Criswell, J. G., DIR: 75
 Crossley, D. A., Jr., GCC: 181
 Crosson, P. R., DET: 34
 Crowe, J. P., DET: 187
 Crutcher, H. L., INF: 10, 114, 116, 120,
 126
 Crutzen, P. J., GCC: 120, 121, 124, 126,
 177, 188, 202, 263; INF: 195, 196,
 197, 198, 199, 209, 210, 213, 221, 223
 Culp, G., DET: 34
 Cummings, M. B., DIR: 238
 Cummings, R. G., DET: 34
 Cunningham, G. L., DIR: 44
 Cunningham, R. K., GCC: 122
 Cunningham, W. M., INF: 136
 Cunnold, D. M., INF: 195
 Cuong, N.-B., INF: 200
 Cure, J. D., GCC: 4; DIR: 56, 111, 175,
 177, 178; DET: 4, 19, 25, 31, 55, 150,
 151, 159, 160, 161, 173, 197
 Currie, J. W., DET: 195
 Curtis, A. R., INF: 34
 Curtis, J. T., DET: 151
 Cushing, D. H., DET: 108, 110, 111,
 113, 125, 133, 139
 Czeplak, G., GCC: 146, 165, 166
 D'Agati, A. P., INF: 39
 Dahlman, R. C., DIR: 101
 Dale, M. B., DIR: 36
 Dale, R. F., PRO: 34
 Daley, P. F., DIR: 182
 Dambara, T., GLA: 78
 Danielson, R. E., DIR: 70
 Danish Meteorological Institute, PRO:
 122, 123
 Dansgaard, W., PRO: 6, 64; GLA: 9
 Darrah, L. L., DET: 76
 Dasvarma, G. L., DET: 184
 Dave, J. V., INF: 46
 Davey, F. J., GLA: 178
 David, T. W. E., GLA: 122, 123
 Davies, R., INF: 49
 Davies, W. J., DIR: 27;
 Davis, M. B., GCC: 266; DET: 152, 158
 Dayan, E., DIR: 44
 Decker, W. L., DIR: 187, 192, 196, 198;
 DET: 77, 81, 82
 DeCloux, R. J., DET: 184
 DeCormis, L., DIR: 14
 Deepak, A., INF: 199
 Deevey, E. S., GCC: 180, 186
 Deevey, E. S., Jr., INF: 250
 Degens, E. T., GCC: 95, 179, 180, 203,
 257, 296
 Dehsara, M., DET: 41
 DeJong, T. M., DIR: 17
 Delany, A. C., INF: 201
 Delaune, R. D., GCC: 97
 Del Castillo, D., DIR: 70
 Delistraty, D. A., DET: 99
 Delmas, R. J., GCC: 32
 DeLucia, E. H., DIR: 111, 122, 123, 126,
 231, 232, 233
 DeLuisi, J. J., GCC: 40; INF: 38
 Demoussy, E., DIR: 55
 Denton, G. H., INF: 246, 249
 Department of Energy, PRO: 7
 de Ruiter, H. E., GCC: 21; DIR: 67, 71,
 75, 113, 216, 224, 226, 227, 229, 235,
 236, 266, 267, 268, 271, 272
 Desjardins, R. L., DIR: 25
 Detling, J. K., DIR: 44
 Dettwiler, J., PRO: 31, 36
 Detwiler, R. P., GCC: 120, 121, 122, 124,
 126
 Devine, J. D., PRO: 44
 DeVooy, C. G. N., GCC: 89, 97, 180;
 DIR: 181
 Dewey, K. F., PRO: 111, 117; GLA: 241
 de Wit, C. T., DIR: 44
 Dey, B., PRO: 121
 De Zeeuw, C., DET: 147
 Dhrymes, P., DET: 46
 Dianov-Klokov, V. I., INF: 196
 Diaz, H. F., PRO: 154
 Dickinson, R. E., INF: 40, 42, 66, 164,
 206, 208, 209, 216
 Dickman, S. R., GLA: 97
 Dickson, R. R., DET: 108; PRO: 102,
 119, 121; INF: 178
 Dimmick, R. L., DET: 190
 Dingle, A. N., DET: 192
 Dionne, J. C., GCC: 197
 Dittberner, G. J., PRO: 46, 82; INF: 163,
 168
 Ditweiler, D. C., DET: 37
 Dixon, K. R., DIR: 44
 Doake, C. S. M., GLA: 199, 204, 206
 Doberitz, R., PRO: 158
 Doebring, R., DET: 189
 Doherty, G. M., INF: 198
 Dolguishin, L. D., GLA: 326
 Domino, R. P., DET: 84
 Domoto, G. A., INF: 46, 212
 Donn, W., GLA: 104, 105
 Donnell, C. A., PRO: 34
 Donner, L., INF: 207

Dopplick, T. G., INF: 285, 286, 287, 288, 323, 324, 325, 346

Dorman, C., PRO: 152

Dorrer, E., GLA: 182, 185, 186

Dougher, R., GCC: 17

Doupe, D., DET: 177

Döve, H. W., PRO: 38, 57

Dowdeswell, J. A., GLA: 225

Downs, R. J., DIR: 13

Downton, W. J., DIR: 122, 123

Doxiadis, C. A., DET: 32

Doyle, F. J., GLA: 235

Doyle, T. W., DET: 158

Dracup, J. A., DET: 41

Drake, B. G., DIR: 60

Draper, N., DIR: 41

Drayson, S. R., INF: 33

Drewry, D. J., PRO: 111; GLA: 29, 173, 174, 198, 233, 235, 237, 242, 318, 326

Driessen, P. M., GCC: 198

Driscoll, D. M., DET: 181

Dronia, H., PRO: 34, 35, 63, 68

Drozdov, O. A., INF: 244

Druffel, E. M., GCC: 36, 49, 92, 93, 95, 150, 180

Dryssen, D., DIR: 3, 4

Duce, R. A., INF: 200

du Cloux, H., DIR: 120, 264

Dudley, E. F., DET: 180

Dumas, M. J., GCC: 177, 205

Duncan, W. G., DIR: 65, 83

Dunkerton, T. J., INF: 213

Dunnigan, M. G., DET: 179

Dunning, J. A., DIR: 75

Dunwiddie, P. W., PRO: 44

Du Pasquier, L., GLA: 216

Durno, S. E., GCC: 197, 198

Durruty, P., DET: 184

Duvick, D. N., GCC: 191; DET: 76

Dyer, M. I., GCC: 186, 199, 200

Dyer, T. G. J., PRO: 157, 158

Dykeman, W. R., GCC: 132

Dyson, F. J., GCC: 266

Dziewonski, A. M., GLA: 100

Eagleson, P. S., DET: 25, 29, 31, 33, 42

Eavis, B. W., DIR: 70

Eckel, O., PRO: 129

Eddy, J. A., PRO: 46; INF: 166, 202

Edmonds, J. A., GCC: 75, 79, 217, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 230, 234, 236, 238, 240, 241, 243, 249, 250, 258, 259, 260, 261, 262, 267, 270, 271, 272, 279, 281, 283, 292; DIR: 187, 188; DET: 12

Edwards, G., DIR: 174

Edwards, N. T., GCC: 119

Egli, D. B., DIR: 19, 127, 245

Ehhalt, D. H., GCC: 188; INF: 194

Ehleringer, J. R., GCC: 190, 201; DIR: 114, 230

El-Gabaly, M. M., DET: 46

Ellet, D. J., PRO: 100, 102, 103

Ellingson, R. G., PRO: 167; INF: 33, 38, 39, 40, 49

Elliott, W., PRO: 152

Elliots, W. P., GCC: 18, 30, 49, 66, 127, 153, 257 DIR: 3, 4; DET: 4; INF: 83

Ellis, F. P., DET: 185, 187

Ellis, J. S., INF: 49

Ellis, W., PRO: 34

Ellison, W. D., DET: 44

Ellsaesser, H. W., PRO: 57, 59; INF: 198, 216, 330

Elsasser, W. M., INF: 34

El-Sharkawy, M. A., DIR: 65

Elterman, L., INF: 46

Elwell, H. A., DET: 44

Elwood, J. H., DET: 177

Elwood, J. W., GCC: 198, 255

Emanuel, W. R., GCC: 18, 22, 98, 99, 103, 144, 145, 154, 155, 159, 161, 162, 170, 180, 250, 251, 252, 253, 254, 265, 270, 271, 272, 274, 275, 276, 277; DET: 152, 153, 158, 160, 161, 162, 163, 164

Emerson, S., GCC: 188

Emery, K. O., PRO: 94, 95; GLA: 74, 75, 76, 78, 80

Engelstad, O. P., DIR: 190, 191

England, A. W., GLA: 237

England, J., GLA: 149

Ennever, F. K., GCC: 179, 191

Enoch, H. Z., DIR: 46, 55, 70, 71, 73, 74, 76, 129

Enting, I. G., GCC: 37, 146, 148, 149, 251, 252, 257, 273, 275

Environmental Protection Agency, GLA: 7

Eppley, R. W., GCC: 97; DET: 105

Epstein, E. S., PRO: 79, 81, 82, 102

Erie, L. J., DIR: 193

Esser, G., GCC: 21, 119, 265

Etkins, R., PRO: 102

Evans, L. T., DIR: 13; DET: 76

Evans, N., DET: 38, 45

Fackrell, J. E., DIR: 14, 24, 25

Fairbanks, R. G., GCC: 195

Fairbridge, R., PRO: 94, 95, 96; GLA: 75

Falk, L. A., Jr., DET: 191

Farman, J. C., GLA: 205

Farquhar, G. D., GCC: 29, 119, 131, 159, 162, 295; DIR: 17, 39, 46, 121, 126, 221, 227

Fastook, J. L., PRO: 135; GLA: 53, 56, 120, 280, 281, 282, 286, 325

Favorite, F., DET: 115, 117

Fearnside, P. M., GCC: 267

Feely, R. A., GCC: 53

Feenberg, D., DET: 38

Feigelson, E. M., INF: 313

Fels, S. B., PRO: 21; INF: 33, 34, 210

Fenn, R. W., INF: 45, 46, 47, 200, 201

Ferrigno, J. G., GLA: 237

Fetcher, N., DIR: 44

Ffolliott, P. F., DET: 40, 53

Fiadeiro, M. E., GCC: 169

Fick, G. W., DIR: 44

Field, C., DIR: 17

Fiering, M. B., DET: 30, 34, 41

Fine, R. A., GCC: 179

Finn, G. A., DIR: 132

Fischer, R. A., DIR: 70, 71, 265

Fisher, D. A., GLA: 145, 152

Fisher, R. F., GCC: 122

Fishman, J., INF: 196, 197, 207, 209, 223

Flanagan, P. W., DIR: 135, 141

Flannery, B. P., PRO: 47, 77, 79, 165, 184

Flaxman, E. M., DET: 44

Fleegler, F. M., DET: 184

Fleer, H., PRO: 158, 159

Fletcher, J. O., PRO: 32, 40, 65

Flint, E., DIR: 6, 18, 67, 111, 113, 157, 158, 159, 160, 162, 223, 225, 226, 249, 250, 251, 253, 256, 257

Flint, M. L., DET: 83

Flint, R. F., INF: 250; GLA: 43, 85, 258

Flohn, H., GCC: 182; INF: 41, 241

Flyger, H., INF: 200, 201

Fobes, C. B., PRO: 130

Foldvik, A. T., GLA: 20, 118, 119, 275

Foley, H. M., INF: 210

Folk, G. E., DET: 188

Folk, H., DIR: 126

Folland, C. K., PRO: 31, 32, 39, 48, 57, 59, 61, 62, 63, 65, 75, 76, 99, 100, 104; INF: 12, 160

Food and Agriculture Organization of the United Nations, GCC: 117, 121, 122, 123, 124, 127, 128, 133; DET: 99

Ford, M. A., DIR: 6, 67, 68, 69, 70, 71, 73, 112, 113, 114, 218, 219, 220, 223

Ford, M. J., DET: 192

Forel, F.-A., GLA: 216

Forrester, J. W., DIR: 36

Foster, J. L., PRO: 117, 121

Foster, T. D., GLA: 116, 119, 123

Foukal, P., INF: 201

Fountain, A. G., GLA: 52

Fournier, R. O., DET: 125

Fowle, F. E., PRO: 42

Fox, H., DET: 44

Fox, P. T., PRO: 32

Foyer, C. H., GCC: 201

Fraiser, G. W., DET: 39

Frakes, L. A., INF: 240

Francey, R. J., GCC: 29, 36, 45, 47, 119, 131, 159, 162, 295

Francis, R. C., DET: 108, 113, 127

Frankignoul, C., PRO: 8; GLA: 106
 Franklin, B., PRO: 42
 Franklin, J. F., GCC: 199
 Fraser, P. J., GCC: 6, 18, 30, 36, 37, 44, 145; INF: 194
 Fraser, R. S., INF: 201
 Freeman, M., DET: 38
 French, H. M., PRO: 130, 131
 Frey, N., DIR: 188, 189
 Frey, N. M., DIR: 70
 Freyer, H. D., GCC: 20, 29, 36, 37, 130, 159, 161, 251, 252, 263, 267, 270, 272, 295
 Friedli, H., GCC: 29, 251
 Frisbie, R., DIR: 192, 193
 Fritts, H. C., GCC: 263; DET: 150
 Fröhlich, C., INF: 201
 Fröhlich, R., GLA: 198
 Fry, F. E. J., DET: 105
 Frydrych, J., DIR: 69, 123
 Fukai, S., DIR: 44
 Fulbright, D. C., PRO: 154
 Fulton, J. D., DET: 190
 Fung, I. (I. Y.-S.), GCC: 42, 131, 132, 167, 168; DIR: 179
 Furcolow, M. L., DET: 191
 Gaastra, P., DIR: 57
 Gade, H. G., GLA: 123
 Gaffney, J. S., GCC: 179, 188
 Gage, K. S., INF: 202
 Gale, J., DIR: 76, 139
 Gammelsrod, T., PRO: 100, 103; GLA: 120, 123
 Gammon, R. H., GCC: 38, 47, 49, 50, 51, 53, 90, 92, 94
 Gamper, M., PRO: 134, 136
 Gandin, L. S., PRO: 38
 Garbutt, K., DIR: 160, 161, 162, 168
 Garcia, R. R., INF: 203
 Gardner, F. G., DIR: 56
 Gardner, R., GCC: 188, 223, 273, 274; DIR: 6
 Gardner, R. H., DIR: 45
 Garnham, P. C. C., DET: 194
 Garrels, R. M., GCC: 9, 97, 182, 185, 192, 193, 194, 196, 203; DET: 137
 Garrett, C., INF: 179, 181
 Gates, C. T., DIR: 59
 Gates, D. M., GCC: 262; DIR: 6, 75, 178
 Gates, W. L., DET: 55; INF: 6, 60, 62, 63, 66, 71, 72, 73, 74, 75, 76, 77, 87, 94, 96, 97, 104, 106, 115, 120, 121, 126, 242, 346, 352; GLA: 268
 Gathman, S. G., INF: 201
 Gaudry, A., GCC: 145
 Gavin, J., PRO: 117, 126; GLA: 243
 Geiger, A. F., DET: 44
 Geiger, D. R., DIR: 113
 Geisler, G., DIR: 70
 Geller, M. A., INF: 211
 Gentile, J., PRO: 158
 Gerbaud, A., DIR: 263
 Gerber, H. E., INF: 200
 Gerland, E., PRO: 31
 Ghan, S. J., INF: 342, 354; GLA: 268
 Ghil, M., PRO: 112, 115
 Gholz, H. L., GCC: 122
 Giaquinta, R. T., DIR: 113
 Gibbons, A. B., PRO: 134
 Gibbs, R. J., GCC: 96
 Gifford, R. M., GCC: 21; DIR: 63, 67, 68, 71, 72, 73, 74, 111, 112, 113, 120, 126, 127, 129, 130, 176, 177, 178, 181, 194, 195, 216, 219, 220, 221, 222, 225, 226, 227, 232, 237, 239, 240, 243, 244, 264, 265, 266, 267, 268, 269, 270, 272
 Gilbert, F., GLA: 100
 Gilbert, L. E., GCC: 200
 Gilchrist, A., INF: 98
 Gildersleeves, P. B., PRO: 31, 42, 82
 Gill, A. E., GLA: 121
 Gill, C. J., DET: 152
 Gille, J. C., INF: 33, 38, 39
 Gilles, H. M., DET: 194
 Gillette, D. A., GCC: 54, 131; INF: 201
 Gilliland, R. L., PRO: 31, 47, 82, 83, 84; INF: 163, 166, 171, 182, 183
 Gilmanov, T. G., DIR: 44
 Gilmour, C. M., DIR: 132
 Giovinetto, M. B., GLA: 172, 185, 186, 210
 Gisser, M., DET: 38
 Gleason, P. G., GCC: 198
 Glen, J. W., GLA: 281, 293
 Global Atmospheric Research Programme, INF: 60
 Glover, T. D., DET: 176
 Glubczynski, A., GCC: 122
 Gold, H. J., DIR: 45
 Gold, L. W., PRO: 132
 Goldemberg, J., GCC: 282
 Goldenberg, S. D., INF: 158, 164, 170; GLA: 268
 Goldman, A., PRO: 23
 Goldstein, I. F., DET: 183
 Goodison, B. E., PRO: 117
 Goodman, B. M., PRO: 45, 46, 82
 Goodman, H. S., GCC: 45
 Goodwin, C. W., PRO: 132, 133
 Goody, R. M., INF: 31, 33, 299
 Gordon, A. F., PRO: 125
 Gordon, A. L., GLA: 50, 116, 120, 124, 309
 Gordon, D. C., Jr., GCC: 180
 Gore, A. J. P., GCC: 198
 Gornitz, V. L., PRO: 95
 Gornitz, V. S., GLA: 74, 75, 93
 Goudriaan, J., GCC: 21, 267, 272, 273, 274, 277, 279, 280; DIR: 67, 71, 75, 113, 121, 127, 176, 216, 222, 224, 226, 227, 229, 235, 236, 266, 267, 268, 271, 272
 Gould-Stewart, S., INF: 198
 Gover, M., DET: 185, 186, 187, 188, 189
 Grable, A. R., DIR: 70
 Grace, J. B., DIR: 165
 Graedel, T. E., INF: 196, 200
 Grainger, R. J., PRO: 118
 Grams, G. W., INF: 47, 201
 Gras, J. L., INF: 201
 Grassl, H., INF: 46
 Grave, N. A., PRO: 131
 Gray, B. M., PRO: 31
 Green, K., DIR: 175, 177
 Greenberg, J. P., INF: 195, 196
 Greenland, D. J., GCC: 122
 Greenwood, P., DIR: 14
 Greischar, L. L., GLA: 188, 317, 318
 Greve, W., DET: 109
 Gribbin, J., GCC: 257
 Grice, G. D., DET: 137
 Grier, C. G., DET: 35
 Griffin, D. M., DET: 151
 Groisman, P. Ya., PRO: 31, 64, 82, 83; INF: 163, 244
 Gross, L., DIR: 39
 Grosval'd, M. G., PRO: 135
 Gruza, G. C., PRO: 38, 57, 58, 59, 156, 159
 Gsell, W. L., GLA: 117
 Guetter, P. J., INF: 242, 252
 Guinn, G., DIR: 57, 58
 Gulland, J. A., DET: 99, 103, 110
 Gulmon, S. L., GCC: 200
 Gundestrup, N. S., GLA: 167, 168
 Gupta, A., DET: 44
 Gupta, V. R., DET: 59
 Gutenberg, B., PRO: 95; GLA: 75
 Gwilliam, W. J., GCC: 179, 203
 Haakensen, N., GLA: 222
 Haan, C. T., DET: 82
 Haas, H. J., GCC: 122
 Haeberli, W., GLA: 218, 220, 221, 226, 232, 237, 251
 Haefele, W., GCC: 218, 221, 222, 229, 230, 233, 236, 238, 239, 240, 241, 262, 279, 281
 Haex, A. J. Ch., DIR: 3, 4, 181
 Hahn, D. G., PRO: 119, 121; INF: 75, 242, 251
 Haines, E. B., GCC: 97
 Haines, W. E., GLA: 120, 121, 123
 Hajek, E. R., DET: 176
 Hale, M. G., DIR: 133
 Hall, A. E., DIR: 42, 46
 Hall, C. A. S., GCC: 53, 120, 122, 131
 Hall, M. C. G., INF: 295, 345, 346, 350, 351, 353, 354, 355, 357, 358
 Halter, B., GCC: 145
 Hambrey, M. J., GLA: 287

Hameed, S., INF: 207, 208
 Hamley, T., GLA: 174
 Hammer, C. U., PRO: 44, 46, 64, 83
 Hammond, R. P., INF: 213
 Hampicke, U., GCC: 120; DIR: 179
 Han, Y.-J., INF: 72, 144; GLA: 268
 Hancock, J. G., DIR: 192
 Hand, D. W., DIR: 71
 Hänel, G., INF: 200
 Hänel, R. A., PRO: 25
 Hanna, S. R., DIR: 24
 Hannah, L. C., DIR: 189
 Hansen, A. D. A., INF: 200
 Hansen, B. L., GLA: 167, 268
 Hansen, J. B., DET: 179
 Hansen, J. E., GCC: 3, 202; DET: 15, 150; PRO: 31, 36, 38, 39, 42, 57, 58, 59, 60, 61, 62, 75, 76, 79, 81, 82, 83, 84, 114, 129; INF: 32, 33, 42, 43, 44, 47, 49, 65, 84, 87, 90, 95, 97, 100, 108, 109-112, 113, 114, 115, 116, 117, 120, 121, 122, 124, 127, 128, 130, 131, 132, 133, 134, 135, 137, 138, 140, 142, 144, 155, 156, 158, 163, 164, 165, 166, 170, 171, 172, 173, 176, 179, 181, 182, 183, 199, 200, 216, 222, 240, 242, 243, 284, 292, 295, 297, 298, 300, 301, 302, 305, 314, 315, 323, 325, 326, 327, 329, 332, 344, 345, 346, 349, 351, 357; GLA: 40, 261, 262, 301
 Hansen, W. R., DIR: 70
 Hanson, A. J., GCC: 198
 Hanson, K. J., GCC: 49
 Hansson, I., GCC: 86
 Hardman, L. L., DIR: 71, 251, 255, 258, 260
 Hardy, R. W. F., DIR: 14, 69, 75, 132, 134, 139, 191, 251, 253, 255, 258
 Hare, E. H., DET: 184
 Harley, W. S., PRO: 67, 68
 Harmsen, G. W., DIR: 133
 Harper, G. J., DET: 191
 Harper, L. A., DIR: 5, 14, 24
 Harris, J. M., GCC: 38, 41, 42, 44, 48, 50, 51, 53, 132, 145
 Harris, S. A., PRO: 132
 Harris, W. F., GCC: 119
 Harrison, H., INF: 223
 Harrison, S., INF: 252
 Harshvardhan, INF: 46, 47, 48, 49, 50, 212
 Hart, G., GCC: 122
 Hartmann, D. L., PRO: 113; INF: 50
 Hartmann, H. D., DIR: 6
 Hartzell, F. Z., PRO: 34
 Harvey, C. N., DIR: 69, 113
 Harvey, L. D. D., INF: 155, 158, 159, 161, 164, 166, 170, 173, 179, 183, 186
 Hasanuma, K., PRO: 95
 Hasen clever, H. F., DET: 191, 192
 Hashimoto, T., DET: 30, 34, 58
 Hastenrath, S., INF: 248, 249; GLA: 222
 Hatch, M. D., GCC: 190
 Hattersley-Smith, G., GLA: 149
 Haurwitz, F., INF: 33
 Haurwitz, M. W., INF: 202
 Havelka, U. D. K., DIR: 14, 57, 59, 69, 75, 132, 134, 139, 191, 251, 253, 255, 258, 264, 266, 268, 271
 Hay, S., DET: 177
 Hay, W. W., GCC: 192
 Hayashi, Y., PRO: 151
 Hayes, D. E., GLA: 178
 Hayes, M., DET: 105
 Haynes, D. L., DET: 84
 Haynes, R. A., DIR: 6
 Hays, J. D., INF: 240, 250
 Heady, E. O., DIR: 191; DET: 44, 45
 Heagle, A. S., DIR: 14, 23
 Heath, D. F., INF: 202, 203, 221
 Heath, O. V. S., DIR: 73
 Heck, W. W., DIR: 23, 75
 Heede, R., GCC: 75
 Heggestad, H. E., DIR: 23
 Heichel, G. H., DIR: 6, 189
 Heim, R. J., PRO: 111, 117; GLA: 241, 242
 Heimann, M., GCC: 127, 146, 165, 167, 168, 250, 254, 255, 256, 257, 274, 277, 280
 Hein selman, M. L., GCC: 197, 198
 Heintz, H. T., DET: 38
 Heintzenberg, J., INF: 200, 201
 Helfand, L. A., DET: 185, 187, 188
 Hellmers, H., DIR: 6, 13, 71, 157, 162
 Henderson-Sellers, A., PRO: 115
 Henschel, A., DET: 187, 188, 196
 Herbert, G. A., GCC: 40
 Herman, B. M., INF: 46, 47
 Herman, G. F., PRO: 114, 126
 Herold, A., DIR: 113
 Herring, J. R., GCC: 202
 Hesketh, J. D., DIR: 6, 18, 37, 57, 58, 59, 68, 69, 71, 73, 123, 157, 162, 222, 256
 Hess, A. D., DET: 193
 Heusser, C. J., INF: 247
 Heusser, L. E., INF: 247
 Heybroek, H. M., DET: 152
 Heyneman, D., DET: 194
 Hibbert, A. R., DET: 40, 53
 Hibler, W. D., III, PRO: 125, 126, GLA: 125
 Hickey, J. R., INF: 202
 Hickman, H. O., DET: 27
 Hidy, G. M., INF: 200
 High Plains Study Council, DET: 82
 Higuchi, K., PRO: 67, 68
 Hilbert, D., DIR: 121, 142, 143
 Hilde, T. W. C., GLA: 82
 Hill, G. R., DIR: 61
 Hillel, D., DIR: 44
 Hindman, E. E., INF: 200
 Hines, C. O., INF: 202
 Hirschboek, K. K., GCC: 263; PRO: 43, 44
 Hirt, H. F., GCC: 177
 Hitchcock, D., GCC: 205, 300
 Hitchfeld, W., INF: 37
 Hjort, J., DET: 109
 Ho, L. C., DIR: 5, 58, 67, 113
 Hobbie, J., DIR: 176, 182
 Hodges, T., DIR: 44
 Hoff, R., INF: 201
 Hoffer, T., INF: 200
 Hoffert, M. I., GCC: 105, 146, 148; PRO: 47, 77, 79, 165; INF: 154, 155, 157, 158, 159, 162, 164, 170, 171, 172, 173, 174, 179, 181, 183; GLA: 268
 Hoffman, G. J., DET: 45
 Hoffman, J. S., DIR: 198; PRO: 94, 184; INF: 170; GLA: 233
 Hofmann, D. J., INF: 199
 Hofstra, G., DIR: 18, 57, 58, 68, 69, 73, 123, 256
 Hogg, R. V., GLA: 86
 Hoinkes, H. C., PRO: 134, 135, 136
 Hojmark Thomsen, H., GLA: 156, 160, 161, 162, 165, 166, 168
 Holdridge, L. R., GCC: 116, 265; DET: 153
 Holdsworth, G., GLA: 125, 287
 Holeman, J. N., DET: 44, 45
 Holland, H. D., GCC: 177, 181, 184, 192; DET: 100
 Holland, W. R., GCC: 169
 Hollin, J. T., PRO: 134; GLA: 43, 46, 242
 Holloway, J. L., Jr., PRO: 114; INF: 10, 11
 Holm, A., PRO: 100, 103
 Holmgren, B., PRO: 120
 Holm-Hansen, O., DET: 103
 Holt, D. A., DIR: 44
 Holt, S. J., DET: 98, 99, 109
 Holtzscherer, J. J., GLA: 155
 Holy, M., DET: 32
 Holzhauser, H., GLA: 224
 Honma, S., DIR: 14
 Hoover, G. M., INF: 35
 Hoover, W. H., DIR: 263
 Hope-Simpson, R. E., DET: 183, 192
 Hopkinson, J. M., DIR: 113
 Horr, W. H., DET: 191
 Horton, J. S., DET: 40
 Horvath, S. M., DIR: 134, 140, 162
 Hoshi, K., DET: 33, 47
 Hoshiai, M., PRO: 31, 36, 58, 59
 Hottel, H. C., INF: 34
 Hou, L., DIR: 75

Houde, E. D., DET: 110
 Houghton, J. T., PRO: 25; INF: 31, 37, 60, 66
 Houghton, R. A., GCC: 18, 19, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 130, 131, 143, 144, 147, 159, 162, 163, 250, 252, 253, 257, 272, 273, 294; DIR: 137, 182
 Howarth, P. J., GLA: 226
 Howe, S. E., INF: 247
 Howell, R. K., DIR: 23
 Hoyt, D. B., PRO: 46, 84
 Hoyt, D. V., INF: 166, 202
 Hoyt, W. G., DET: 41
 Hozumi, K., DIR: 65
 Hsieh, A. C. L., DET: 177
 Hsieh, C. T., INF: 161
 Hsiung, J., PRO: 99
 Hsu, K. J., GCC: 195
 Huber, S. C., DIR: 58, 59, 247
 Huck, M. G., DIR: 17, 44
 Hudson, S. H., INF: 202
 Hugenholtz, P. G., DET: 192
 Hughes, A. P., DIR: 67, 71, 72
 Hughes, M. K., PRO: 6
 Hughes, T. J., PRO: 112, 135; INF: 246, 249; GLA: 46, 120, 185, 280, 281, 287, 320, 325, 327
 Huke, R. F., DET: 4
 Hummel, J. R., INF: 87, 292, 300, 301, 302, 307, 308, 346
 Humphreys, W. J., PRO: 42, 57
 Hunt, B. G., INF: 87, 164, 240, 292, 297, 300, 301, 302, 307, 308, 346; GLA: 268
 Hunt, J. M., GCC: 203
 Hunt, R. D., DET: 191
 Hunter, J. R., DET: 110
 Huntley, B., INF: 247, 248
 Hurd, R. G., DIR: 67, 68, 70, 73, 74, 126
 Hurley, T. J., III, GCC: 280
 Hurst, H. E., DET: 41
 Hurt, P., DIR: 6, 175, 177
 Husar, R. B., INF: 200
 Hutchinson, G. E., GCC: 177, 202, 205, 300
 Huttinger, W. D., GCC: 122
 Hydrographischer Dienst in Österreich, PRO: 117
 Hyslop, N. St. G., DET: 190, 191
 Hyson, P., GCC: 37, 38, 45, 53, 54, 55, 119, 131, 132, 146, 165, 166; DIR: 179
 IASH (ISCI) - UNESCO, GLA: 140, 217
 Idso, S. B., GCC: 262; DIR: 4, 61, 126, 138, 139, 187, 188, 193, 196, 197, 198, 199; DET: 35; PRO: 151, 160; INF: 288, 323, 324, 326, 327, 328, 329, 330, 331, 346
 Iken, A., GLA: 145
 Imai, K., DIR: 67, 68, 71, 75, 123, 218, 219, 221, 223, 224, 225, 226, 228, 238, 239, 240, 241, 249, 251, 253
 Imbrie, J., GCC: 190; PRO: 6; INF: 247
 Imbrie, J. Z., GCC: 190; PRO: 6
 Incoll, L. D., DIR: 58
 Ingham, M. C., DET: 100, 110, 113
 Ingle, S. E., GCC: 88
 Ingraham, W. J., Jr., DET: 114, 115, 122
 Ingram, K. T., DIR: 44
 Inn, E. C. Y., INF: 198
 International Horticultural Congress, DIR: 3
 Itek Optical Systems, GLA: 235
 Ivins, E. R., GLA: 143
 Iwashima, T., PRO: 58, 59, 61
 Jacka, T. H., PRO: 123; GLA: 172, 173, 175
 Jackson, Col., PRO: 130
 Jacobs, S. S., GLA: 50, 117, 118, 119, 120, 121, 122, 123, 309, 326
 Jacobson, M. B., DIR: 148
 Jaeger, G., DIR: 133
 Jaeger, J., GCC: 242
 Jaeger, L., INF: 114, 117, 122, 126
 Jaenicker, R., INF: 201
 Jäger, J., PRO: 31, 64; INF: 241, 244
 Jagner, D., DIR: 3, 4
 Jahr, D., DET: 71, 72
 James, L. D., DET: 43
 James, R. W., PRO: 32
 Janerich, D. T., DET: 184
 Janzen, D. H., GCC: 200
 Japan Meteorological Agency, PRO: 118
 Jarrett, J., GCC: 217, 242
 Jarvis, P. G., DIR: 59
 JASON, GCC: 217, 218, 221, 222, 231, 260, 262
 Jeannin, P. F., GLA: 121, 214
 Jenkins, W. J., GCC: 91
 Jenne, R. L., PRO: 36, 48, 137, 138; INF: 114, 116, 299
 Jenny, H., GCC: 181, 194
 Jensen, M. E., DIR: 197
 Jezek, K. C., GLA: 31, 54, 178, 179, 183, 190, 317, 319, 326
 Johnsen, S. J., GLA: 190
 Johnson, A. H., GCC: 266; DET: 151, 161
 Johnson, A. I., PRO: 32
 Johnson, C., INF: 116, 349
 Johnson, C. M., PRO: 111, 113, 126, 127; GLA: 242, 243
 Johnson, D. R., INF: 38
 Johnson, I. R., DIR: 44
 Johnson, K., PRO: 73
 Johnson, W. C., GCC: 117, 120, 125; DET: 152
 Johnson, W. M., DET: 28
 Johnson, W. T., PRO: 114
 Johnston, H. S., INF: 210
 Johnston, J. E., DET: 176
 Jolliffe, P. A., DIR: 263
 Jones, C. H., DIR: 236
 Jones, D., GLA: 173, 174, 175
 Jones, J. W., DIR: 19, 20, 44, 58, 60, 62, 65, 66, 68, 71, 74, 112, 194, 195, 197, 245, 246, 248, 253, 254, 255, 256, 257, 258, 259
 Jones, P., DIR: 19, 20, 37, 58, 60, 61, 62, 65, 66, 68, 71, 74, 112, 194, 195, 197, 245, 246, 248, 253, 254, 255, 256, 257, 258, 259
 Jones, P. D., DET: 162; PRO: 31, 35, 36, 38, 39, 41, 45, 46, 48, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 70, 75, 76, 77, 80, 81, 84, 99, 123, 124; INF: 12, 151, 183, 243, 244
 Jones, R., GCC: 251
 Jones, T., DET: 187, 188
 Jones, V., DET: 77
 Joseph, J. H., INF: 32
 Junge, C. E., GCC: 146, 165, 166; INF: 200, 201
 Jurik, T. W., DIR: 73, 120, 175, 178
 Jurva, R., PRO: 122
 Kac, M., DIR: 36
 Kagann, R. H., INF: 222
 Kaitala, V., DIR: 46
 Kalinan, G. P., DET: 32
 Kalisch, R. B., GCC: 72
 Källén, E., INF: 155, 163
 Kamanina, M. S., DIR: 113
 Kamb, B., GLA: 51
 Kanamitsu, M., PRO: 157
 Kandel, R. S., INF: 154, 323, 332, 346
 Kanemasu, E. T., DIR: 44, 111
 Kaplan, L. D., INF: 37
 Kappen, L., DET: 151
 Karapet'iants, E. H., PRO: 118, 120
 Karl, T., PRO: 154
 Karnig, J. J., DET: 151
 Kasser, P., GLA: 216, 218, 235
 Kasting, J. F., GCC: 194
 Katayama, A., INF: 352, 353, 360
 Katayama, K., DET: 178, 181, 183
 Kates, F. E., PRO: 39, 57, 61, 100
 Kates, R. W., DET: 3, 6, 42, 43
 Kato, T., GLA: 78
 Kats, G., DIR: 23
 Katz, R. W., INF: 100
 Katzenelson, E., DET: 190
 Kauppi, P., GCC: 265
 Kay, P. A., INF: 247
 Keeling, C. D., GCC: 3, 5, 18, 27, 36, 37, 38, 40, 44, 45, 48, 50, 52, 53, 54, 55, 65, 66, 68, 69, 70, 98, 101, 102, 119, 130, 131, 132, 143, 144, 146, 147, 148, 158, 159, 165, 166, 167, 168, 217, 218, 222, 231, 240, 250, 257, 268, 269, 270, 274, 275, 280; DIR: 42, 137, 174, 177, 178, 179 DET: 11 INF: 164

Keepin, W., GCC: 217, 222, 226, 239
 Keir, R. S., GCC: 192
 Keliher, T. E., PRO: 113
 Keller, C. A., DET: 184
 Kelley, J. J., GCC: 119
 Kellogg, T. B., GLA: 120, 282
 Kellogg, W. W., GCC: 242, 266; PRO: 31, 64, 112, 114, 128; INF: 239, 241, 244, 246, 247, 249
 Kelly, P. M., PRO: 31, 35, 39, 42, 57, 58, 59, 61, 63, 64, 75, 76, 78, 84, 123, 124, 127; INF: 199, 243, 244
 Kelso, M. R., DET: 34
 Kempe, S., GCC: 96, 97, 179, 255, 257
 Kendall, S. B., DET: 194
 Kepert, D. G., DIR: 132
 Kercher, J. R., DIR: 44
 Kerr, R. A., INF: 240
 Kerschner, H., GLA: 217
 Kesler, C. M., GLA: 147
 Ketner, P., GCC: 21, 267, 272, 273, 274, 277, 279, 280, 296
 Key, J., DIR: 77
 Keyes, D., GCC: 3, 11, 219, 227, 228, 230, 234, 241, 242, 260, 276, 278, 279, 280, 281; INF: 170, 174
 Khalil, M. A. K., GCC: 36, 188; INF: 194, 195, 196
 Khodakov, V. J., PRO: 136
 Kidson, J., PRO: 156, 157, 158, 159
 Kiehl, J. T., PRO: 15, 19, 20; INF: 34, 35, 36, 37, 42, 43, 294, 295, 299, 300, 333, 334
 Kilbourne, E. M., DET: 188
 Killough, G. G., GCC: 98, 99, 101, 102, 103, 153, 154, 155, 180, 250, 251, 252, 253, 254, 270, 272, 274, 277
 Killworth, P., GLA: 118
 Kimball, B. A., DIR: 14, 21, 42, 55, 61, 71, 72, 111, 120, 126, 130, 131, 133, 139, 140, 157, 174, 176, 177, 178, 188, 189, 190, 191, 193, 194, 195, 196, 198
 Kincer, J. B., PRO: 57
 King, D. A., DIR: 43
 Kington, J. A., PRO: 31, 32
 Kinsey, D. W., GCC: 180
 Kipp, N. G., INF: 247
 Kira, T., DIR: 65
 Kirk, B. L., GCC: 292
 Kirkham, M. B., DIR: 111
 Kito, H., DET: 178
 Kivinen, E., GCC: 197
 Klein, E., PRO: 111
 Klein, W. H., PRO: 26
 Klemes, V., DET: 31, 41, 56
 Klimish, R. L., INF: 200
 Kloss, M., DIR: 132, 133
 Kluge, M., GCC: 191
 Knecht, G. N., DIR: 6, 130
 Kneese, A. V., DET: 37
 Kneip, T. J., INF: 200
 Knox, F., GCC: 33, 192; INF: 240
 Knutzen, J., DET: 105
 Ko, F. K., INF: 222
 Ko, M. K. W., INF: 198
 Koblenz-Mishke, O. J., GCC: 89, 180
 Koch, L., PRO: 64, 122
 Koerner, R. M., PRO: 120, 135; GLA: 143, 145, 146, 147, 149, 152
 Koesoebiono, GCC: 198
 Kohler, M. A., PRO: 35
 Kohlmaier, G. H., DIR: 137, 138, 179
 Koller, H. R., DIR: 58, 113, 121
 Komarek, E. V., DET: 152
 Komhyr, W. D., GCC: 37, 38, 41, 42, 43, 44, 47, 49, 50, 51, 52, 53, 54
 Kondo, K., DET: 110
 Kondratyev, K. Ya., INF: 38, 202
 Kononova, M. M., GCC: 179, 199
 Konyukh, L. A., INF: 46
 Köppen, W., DET: 153; PRO: 38, 57
 Korshover, J., GCC: 49, 50; PRO: 67, 69, 70, 73, 75, 76; INF: 202, 218
 Korzoun, V., INF: 343
 Koscielny, A., PRO: 154
 Kosobud, R. F., GCC: 228, 229, 230
 Kotlyakov, V. M., PRO: 135; GLA: 172, 173, 175, 204, 217
 Kovda, V. A., DET: 42
 Kovyneva, N. P., PRO: 63, 64; INF: 244
 Kozlowski, T. T., DIR: 13; DET: 151
 Kramer, P. J., GCC: 130, 263; DIR: 13, 42, 56, 57, 58, 145, 175, 187, 198
 DET: 151, 161
 Kraus, E. B., PRO: 151, 157, 158, 159; INF: 159
 Krebs, J. E., GCC: 122
 Krebs, O., Jr., PRO: 94, 95; GLA: 75
 Krenke, A. N., PRO: 135, 136; GLA: 217
 Krenzer, E. G., Jr., DIR: 70, 71, 73
 Kretchman, D. N., DIR: 3, 14
 Kriedemann, P. E., DIR: 6
 Krimmel, R. M., GLA: 226, 234
 Krishnamurti, R., PRO: 157
 Kristensen, E. G. M., GLA: 214
 Kristensen, K. J., DIR: 70
 Kristensen, M., PRO: 136
 Krom, M. D., GCC: 97
 Kroopnick, P. M., GCC: 179
 Kruss, P., GLA: 220, 222
 Ku, S. B., DIR: 235, 236
 Kuchler, A. W., DET: 150, 153
 Kuenen, Ph. H., PRO: 95; GLA: 75
 Kuhn, M., PRO: 135; GLA: 220, 249, 255, 256, 257, 261
 Kuhn, P. M., INF: 38
 Kuhn, W. R., INF: 33, 49, 87, 292, 300, 301, 302
 Kukla, G. J., PRO: 6, 35, 111, 113, 117, 118, 119, 120, 126; GLA: 243
 Kunde, V. G., INF: 39
 Kunzi, K. F., PRO: 117
 Kuo, H. H., GCC: 169
 Kuo, J. J., GCC: 169
 Kuo, Y. H., DIR: 133
 Kurtz, D., GLA: 125
 Kutzbach, J. E., INF: 242, 247, 248, 249, 252
 Kvet, J., DIR: 128
 Kvinge, T., GLA: 275
 Labitzke, K., PRO: 73
 Lachenbruch, A. H., PRO: 132; GLA: 243
 Lacis, A. A., INF: 32, 33, 41, 49, 113, 165, 207, 217
 Laevastu, T., DET: 105, 139
 Lake, J. V., DIR: 59
 Lal, M., INF: 87, 292, 302
 LaMarche, V. C., GCC: 21, 263; DIR: 137, 145, 180, 198; DET: 151, 161; PRO: 44, 64
 Lamb, H. H., GCC: 257; PRO: 6, 32, 46, 83, 112, 120, 122; INF: 165, 199
 Lamb, P. J., PRO: 157, 158
 Lambeck, K., PRO: 95
 Lambert, J. R., DIR: 14, 111
 Lamborg, M. R., DIR: 135, 190
 Landsberg, H. E., PRO: 36, 160
 Lane, C., GLA: 235
 Lane, W., DET: 47
 Langbein, W. B., DET: 34, 41, 44
 Langhans, R., DIR: 13
 Langway, C. C., GLA: 156
 Lanly, J. P., GCC: 127
 Lansberg, H. H., GCC: 217, 232, 237, 240
 Larcher, W., DIR: 130
 Larkum, A. W. D., DET: 100
 Larson, L., PRO: 153
 Larson, W. E., DIR: 190, 193
 Lasaga, A. C., GCC: 31, 34, 194, 195, 196, 203, 205
 Lasker, R., DET: 108, 110, 113
 Lattman, L. H., GCC: 118
 Lau, N. C., PRO: 68
 Launder, B. E., INF: 179
 Laurence, J. A., DIR: 14
 Laurmann, J. A., GCC: 268, 269, 270, 271, 272, 274, 277, 278, 280
 Lawson, D., INF: 200
 Layser, E. F., DIR: 198
 Lean, J. L., INF: 202, 203
 Learmonth, A. T. A., DET: 194
 Leavitt, S. W., GCC: 29, 36, 295
 Lebedeff, S., DIR: 196, 197; INF: 130
 Lee, A. R., DET: 176
 Lee, D. H. K., DET: 189
 Lee, J. J., DIR: 14, 24
 Leeper, J., DIR: 192, 193
 Leighton, H. G., INF: 46

Lemke, P., PRO: 121, 125, 126
 Lemon, E. R., GCC: 122; DIR: 4, 24, 43, 55, 60, 65, 77, 78, 120, 173; DET: 150, 151
 Lennon, G. W., GLA: 74
 Lenoble, J., INF: 47, 212
 Leonard, O. A., DIR: 70
 Le Riche, W. H., DET: 179, 181
 Leovy, C. B., INF: 323
 Lerman, A., GCC: 185, 192, 193, 196, 203
 LeTreut, H., PRO: 115
 Lettau, H. H., PRO: 119
 Lettau, K., PRO: 119
 Lettenmaier, D. P., DET: 30, 31, 33, 47
 Levitus, S., GCC: 92; INF: 157, 180, 181
 Levy, H., INF: 208
 Lewis, E. L., GLA: 124, 275, 277
 Lewis, L. J., GCC: 84, 104, 296
 Lewis, R. A., DIR: 14
 Li, J., GLA: 221
 Li, Y.-H., GCC: 100; INF: 179
 Lian, M. S., PRO: 113; INF: 215
 Lichty, R. W., DET: 44
 Lidwell, O. M., DET: 190
 Lieth, H., GCC: 119, 123, 186, 263, 265; DIR: 39
 Likens, G. E., GCC: 97, 115, 116, 119, 121, 123, 126, 128, 132, 143, 180, 294; DIR: 173; DET: 147, 151
 Limbert, D. W. S., PRO: 119, 135; GLA: 246
 Lincoln, D. E., GCC: 263; DIR: 140, 148, 169, 192
 Lind, A. R., DET: 176
 Lindh, T. B., GCC: 192, 193
 Lindzen, R. S., INF: 6, 87, 292, 297, 300, 301, 302, 323
 Lingle, C. S., PRO: 135; GLA: 53, 55, 188, 317, 319, 320, 321, 325, 328
 Linick, T. W., GCC: 96, 150
 Linsley, R. K., DET: 30
 Liou, K.-N., INF: 6, 28, 29, 31, 37, 41, 46, 49, 157
 Lippmann, M., INF: 200
 Lipschultz, F., INF: 197
 Lisitzin, E., PRO: 94, 95; GLA: 73, 75
 Lister, R. A., DIR: 77, 78, 120
 Liu, S. C., INF: 197, 198, 210, 223
 Llewellyn, R. A., INF: 213
 Lliboutry, L., GLA: 222, 225, 252
 Lloyd, C. R., GCC: 195
 Lloyd, S., DET: 181
 Loewe, F., GLA: 156, 160, 172
 Loftin, T., DET: 42
 Logan, J. A., GCC: 188, 263; INF: 196, 197, 199, 210, 223
 Lommen, P. W., DIR: 174
 Londer, R., INF: 163, 240
 London, J., INF: 202
 Long, A., GCC: 29, 36, 295
 Long, M. R., DET: 52
 Loomis, R. S., DIR: 6, 37
 Loomis, W. E., DIR: 130
 Lorian, C., GCC: 29; PRO: 115; GLA: 190
 Loser, K. S., GLA: 210
 Loucks, O. L., GCC: 258
 Lough, J. M., DET: 14; PRO: 40, 64; INF: 244
 Louwerse, W., DIR: 218, 220, 221, 228
 Lovell, R. T., DET: 99
 Lovelock, J. E., GCC: 205, 302
 Lovins, A. B., GCC: 217, 218, 221, 222, 228, 229, 230, 235, 240, 242, 260, 262
 Lovseth, K., GCC: 36
 Lowe, C. R., DET: 179, 181
 Lowenthal, D. H., INF: 201
 Ludecke, H., DIR: 75
 Ludwig, J. H., INF: 46
 Ludwig, L. G., DIR: 42, 46, 65
 Lugina, K. M., PRO: 58, 59, 61
 Lugo, A. E., GCC: 19, 115, 116, 117, 121, 124, 126, 127, 128, 130, 257, 267, 294; DIR: 176
 Lull, H. W., GCC: 122
 Lupton, G., INF: 96, 97, 98, 137, 140, 141
 Luther, F. M., GCC: 3, 296; DET: 4, 11, 13, 14, 25, 54, 90, 150, 160, 173; PRO: 4, 6, 7, 15, 19, 165, 166, 167, 179, 180, 184; INF: 9, 47, 143, 182, 199, 210, 222, 285, 339, 347, 348
 Luthin, J. N., DET: 83
 Lutjeharms, J. R. E., GLA: 74
 Lutz, H. J., GCC: 122
 Luxmoore, R. J., GCC: 263; DIR: 132, 133, 135, 139
 L'Vovich, M. I., DET: 32, 44, 45
 Lyford, W. H., DET: 151
 Lyons, J. B., GLA: 146
 Maas, E. V., DET: 45
 Maas, S. J., DIR: 44
 MacAyeal, D. R., PRO: 135; GLA: 52, 53, 119, 123, 125, 172, 174, 183, 210, 310, 317, 318, 319, 320, 321, 327
 MacCracken, M. C., GCC: 3, 296; DET: 4, 11, 13, 14, 25, 54, 74, 90, 150, 160, 173; PRO: 4, 6, 7, 8, 15, 42, 82, 83, 165, 166, 179, 180, 184; INF: 6, 9, 40, 182, 199, 201, 213, 222, 323, 339
 MacDonald, G. F., INF: 346
 MacDonald, W. R., GLA: 237
 MacDowall, F. D. H., DIR: 72, 73, 266
 Macfarlane, W. V., DET: 176
 Machta, L., GCC: 37, 49, 146, 165, 166, 272, 273; DIR: 3, 4; DET: 4, 11
 Macias, E. S., INF: 200
 MacIntyre, F., GCC: 87
 Mackay, J. R., PRO: 132
 Mackenzie, F. T., GCC: 97, 193; DET: 137
 MacKenzie, G., DET: 177
 MacKinnon, P. K., PRO: 111
 Madden, R. A., PRO: 21, 77, 80, 81
 Maddy, K. T., DET: 192
 Madsen, E., DIR: 5, 58, 121
 Magaritz, M., GCC: 122
 Maier-Reimer, E., GCC: 104, 169
 Maisch, M., GLA: 218, 226
 Maknoon, R., DET: 36
 Male, D. H., PRO: 118
 Malone, R. C., INF: 213
 Malone, T. C., GCC: 97
 Manabe, S., GCC: 3, 265; DIR: 196
 DET: 13, 15, 25, 30, 55, 74, 81, 90, 147, 150, 153; PRO: 65, 72, 113, 114, 128, 129, 151; INF: 10, 11, 30, 31, 36, 37, 49, 70, 74, 75, 86, 87, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109–112, 114, 119, 121, 122, 124, 125, 126, 127, 128, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 175, 176, 206, 208, 215, 239, 242, 243, 245, 249, 251, 290, 291, 292, 295, 296, 297, 298, 299, 302, 305, 307, 308, 309, 310, 314, 315, 326, 327, 329, 330, 332, 333, 346, 350; GLA: 220, 268, 280
 Mandelbrot, B. B., DET: 31, 41
 Mandl, R. H., DIR: 23
 Mankin, J. B., DIR: 41
 Manley, G., PRO: 31, 36, 64, 120
 Mann, L. J., DET: 52
 Manne, A. S., GCC: 219, 229, 233, 237
 Mansfield, W. W., DET: 39
 Mantayla, A., GLA: 104, 116
 Marable, J. H., INF: 340
 Marc, J., DIR: 71, 243
 Marchetti, C., GCC: 240
 Maristany, A. E., DET: 34
 Markell, E. K., DET: 194
 Markley, D. W., GCC: 280
 Marks, P. L., GCC: 122
 Marland, G., GCC: 7, 48, 65, 66, 67, 68, 70, 71, 75, 143, 203, 218, 231, 232, 250, 262, 266, 283
 Marlay, R. C., GCC: 278
 Marmor, M., DET: 188
 Maroulis, P. J., INF: 198
 Marshall, B., DIR: 39, 46
 Martin, J. K., DIR: 133
 Martin, S., GLA: 125, 222
 Marvil, R., INF: 247
 Mass, C., PRO: 31, 42; INF: 163, 199, 348
 Massachusetts Institute of Technology, DIR: 3, 4
 Masters, C. D., GCC: 74, 75

Mata, L. J., DET: 195
 Matalas, N. C., DET: 30, 34, 41, 58
 Mather, J. R., DET: 153
 Mathewes, R. W., INF: 247
 Matson, M., PRO: 115, 117, 120; GLA: 38, 243, 244
 Matson, P. A., DIR: 135
 Matsui, H., DET: 177
 Matthews, E., GCC: 123, 166, 181
 Mattson, W. J., GCC: 199
 Maunder, W. J., DET: 6
 Mauney, J. R., DIR: 57, 58, 68, 69, 111, 192, 230, 231, 232, 234, 243, 246, 250
 Maxon Smith, J. W., DIR: 189
 May, J., DET: 193
 May, R. M., DET: 194
 Maykut, G. A., PRO: 112, 124, 125, 129
 Maynard Smith, J., DET: 128
 Mayo, L. R., PRO: 136; GLA: 222, 246
 McAndrews, J. H., DET: 153
 McCaffrey, R. J., INF: 201
 McCaughran, D. A., DET: 110
 McClatchey, R. S., PRO: 15; INF: 33, 39, 292, 348
 McCloud, D. E., DIR: 44
 McConnell, J. C., INF: 209
 McCormick, R. A., INF: 46
 McCree, K. J., DIR: 13
 McDonald, A. D., DET: 184
 McDowell, L. K., GCC: 197
 McElroy, M. B., GCC: 33, 97, 179, 191, 192; INF: 197, 240
 McEvedy, C., GCC: 251
 McFadden, J. D., PRO: 129
 McGowan, J. A., DET: 108
 McHugh, J. L., DET: 128
 McInturff, R. M., PRO: 73
 McIntyre, N. F., GLA: 233, 235
 McKay, G. A., PRO: 116
 McKee, T. B., INF: 49
 McKeen, S. A., INF: 198, 213
 McKenzie, J. A., GCC: 195
 McKeown, T., DET: 177
 McLain, D. R., DET: 122
 McLaughlin, S. B., GCC: 21, 263; DET: 151, 159, 161
 McLean, D. M., GCC: 195
 McLeod, A. R., DIR: 14, 24, 25
 McMurtrie, R., DIR: 44
 McNaughton, S. J., GCC: 186, 199
 McPhee, M. G., GLA: 278
 McPherson, M. B., DET: 43
 McRae, J. E., INF: 196
 Meade, R. H., GCC: 96, 97
 Meador, W. E., INF: 32
 Meadows, D., GCC: 239
 Medhurst, T. G., GLA: 174
 Medina, E., GCC: 119
 Meehl, G. A., DET: 15, 25, 55; PRO: 79, 114; INF: 90, 91, 92, 93, 94, 97, 100, 104, 105, 106, 108, 109–112, 114, 116, 117, 118, 120, 121, 122, 124, 127, 128, 130, 131, 132, 133, 134, 135, 140, 142, 144, 156, 297, 346
 Meentemeyer, V., GCC: 117, 119; DIR: 139
 Meidner, H., DIR: 73
 Meier, M. F., PRO: 96, 133, 134, 136, 137; GLA: 12, 23, 42, 52, 93, 139, 141, 143, 144, 151, 220, 225, 226, 232, 233, 234, 235, 237, 249, 252
 Melack, J. M., GCC: 95, 119, 126, 195
 Melillo, J. M., GCC: 97, 120, 121, 123, 124, 125, 126, 129; DIR: 134, 139, 148; DET: 158
 Mellor, J. C., PRO: 129
 Mellor, M., GLA: 164, 166, 172, 210
 Mendonca, B. G., GCC: 38
 Menzel, D. W., GCC: 96
 Mercer, J. H., PRO: 133, 135; INF: 163, 241; GLA: 46, 74, 319, 325
 Meserve, J. M., INF: 10, 114, 116, 120, 126
 Mészáros, A., INF: 200, 201
 Mészáros, E., INF: 200
 Meybeck, M., GCC: 95, 96, 97, 119, 126
 Meyer, G. E., DIR: 38, 39, 44
 Meyer, R., GCC: 75, 76
 Meyerhoff, A., GCC: 75
 Meyers, L. E., DET: 39
 Michael, P. A., INF: 151, 162, 169, 174
 Michel, B., PRO: 130
 Michel, R. L., GLA: 123
 Middleton, J. H., GLA: 116
 Middleton, W. E. K., PRO: 32
 Mie, G., INF: 29, 49
 Mielke, D. L., DET: 158
 Mielke, J. E., GLA: 146
 Miles, M. K., PRO: 31, 42, 82
 Miller, F. J., GCC: 30
 Miller, J. E., DIR: 14, 24
 Miller, K. G., GCC: 195
 Miller, P. C., GCC: 119, 120, 130, 131, 133; DIR: 4, 44, 134, 137, 138, 139, 142, 148
 Miller, W. F., DET: 149, 152
 Miller-Alexander, H., DIR: 129, 130, 131
 Millero, F. J., GCC: 5, 90; DET: 100
 Mills, E., DET: 38
 Mills, E. L., DET: 125
 Minchin, P., GCC: 119
 Minnich, R. A., DIR: 138
 Mintz, R., INF: 204
 Mintz, Y., INF: 73, 204, 216
 Mitchell, J. F. B., GCC: 3, 265; DET: 15, 16, 17, 18, 150; PRO: 65, 71, 72, 79, 165; INF: 96, 97, 98, 99, 100, 104, 106, 131, 136, 137, 140, 141, 167, 346, 348
 Mitchell, J. M., Jr., GCC: 202; DET: 34, 41; PRO: 6, 31, 32, 33, 34, 35, 38, 43, 46, 57, 63, 76, 82, 99, 154, 155; INF: 46
 Mitchell, S. T., DIR: 72
 Mix, A. C., INF: 247, 249
 Miyakoda, K., PRO: 111
 Mobley, R. L., INF: 116, 120
 Mock, S. J., GLA: 156, 166, 167
 Moehring, D. M., DET: 150
 Moeller, H., DET: 111
 Mohren, G. M. J., DIR: 44
 Molina, M. J., INF: 195, 209
 Möller, C., GCC: 122
 Möller, F., DET: 13; INF: 11, 285, 286, 287, 288, 346
 Molnar, G., INF: 202, 205, 206, 221, 222
 Molofsky, J., GCC: 120, 121, 124, 126
 Momiyama (Sakamoto), M., DET: 178, 181, 183
 Monsi, M., GCC: 190
 Monteith, J. L., GCC: 119
 Mook, W. G., GCC: 37, 45, 159, 167
 Mooley, D. A., PRO: 156, 157
 Mooney, H. A., GCC: 200; DIR: 17, 177
 Moor, E., GCC: 29
 Moore, B., GCC: 120, 121, 127, 162
 Moore, P. D., GCC: 197
 Moore, R. E., DET: 187
 Mopper, K., GCC: 180
 Morey, H. G., GCC: 122
 Morgan, J. J., DET: 100, 102, 105
 Morgan, J. V., DIR: 72
 Morgan, V. I., GLA: 123, 172, 173, 175
 Morison, J. I. L., DIR: 63, 67, 68, 112, 120, 126, 127, 194, 216, 219, 220, 222, 225, 226, 227, 232, 237, 239, 240, 243, 244, 266, 267, 269
 Mörner, N. A., GLA: 83
 Morris, J. T., DIR: 44
 Mortensen, L. M., DIR: 120, 127, 132
 Mortimer, D. C., DIR: 230
 Morton, F. I., DET: 39
 Morton, J., DET: 178, 181, 183, 184
 Moses, H., PRO: 7, 82
 Moss, D. N., DIR: 17, 19, 57, 61, 70, 71, 73, 112, 221, 222, 223, 227, 228, 263, 269
 Mostek, A., PRO: 154
 Mount, L. E., DET: 76
 Mouteney, S. N., GLA: 85
 Mulholland, P. J., GCC: 96, 197, 255
 Müller, F., PRO: 134; GLA: 147, 216, 217, 218, 223, 235, 287
 Müller, P., INF: 179
 Müller, P. J., GCC: 96
 Müller, W. J., DIR: 75
 Munk, J. W., GCC: 84, 99
 Munk, W., GCC: 122, 127, 280; PRO: 95; GLA: 94, 97, 98, 99, 100, 102

Munk, W. H., INF: 158
 Munro, J. K., Jr., GCC: 180
 Muntz, A., GCC: 37
 Murata, Y., DIR: 67, 68, 71, 75, 123, 218, 219, 221, 223, 224, 225, 226, 228, 237, 238, 239, 240, 241, 249, 252, 253
 Murphy, A. H., INF: 213
 Musgrave, R. B., DIR: 6, 17, 19, 57, 61, 222
 Myers, N., GCC: 123, 124, 251, 267
 Mysak, L. A., DET: 109, 139
 Nafziger, E. D., DIR: 58, 121
 Nam, J., DET: 183
 Namias, J., PRO: 41, 64, 68, 112; INF: 241, 244
 Nastrom, G. D., INF: 202
 Natarajan, M., INF: 198, 203
 National Academy of Sciences (NAS), GCC: 130; DIR: 4; DET: 4; PRO: 3, 6
 National Aeronautics and Space Administration, PRO: 137; INF: 199
 National Aeronautics and Space Administration Panel for Data Evaluation, INF: 207
 National Defense University, DET: 5
 National Forest Products Association, DET: 149
 National Marine Fisheries Service, DET: 97, 98
 National Oceanic and Atmospheric Administration, DET: 39; INF: 182
 National Research Council, GCC: 3, 11, 23, 125, 182, 188, 201, 240, 242; DIR: 187; DET: 6, 13, 14, 18, 25, 74, 75, 76, 82, 97, 99, 101, 102, 111, 113, 114, 119, 122; PRO: 3, 7, 9, 40, 79, 94, 98, 127, 135, 136, 137, 139, 151, 179; INF: 4, 5, 10, 60, 155, 163, 175, 193, 195, 196, 207, 215, 222, 239, 323, 324, 339, 360; GLA: 237
 National Research Council, see NRC
 Navato, A. R., PRO: 71
 Navy-NOAA Joint Ice Center, PRO: 123
 Naylor, D., GLA: 85
 Naylor, D. J., DIR: 57
 Neal, C. S., GLA: 123, 183
 Neales, T. F., DIR: 58, 112, 265
 Nealy, J. E., INF: 203
 Neave, K. G., PRO: 132
 Neftel, A., GCC: 28, 29, 32, 33, 35, 36, 37, 251, 275; DET: 11; PRO: 79; INF: 239, 240
 Neilson, W. A., PRO: 111
 Neishtadt, M. I., GCC: 197, 198
 Nelson, C. J., DET: 77
 Nelson, F., DET: 185, 187
 Nemejc, J., DET: 34
 Nevin, D. J., DIR: 6
 Newell, R. E., GCC: 47, 49; PRO: 68, 71, 73; INF: 118, 198, 199, 285, 286, 287, 288, 323, 324, 325, 346
 Newhall, C. G., PRO: 42, 43
 Newkirk, G., Jr., PRO: 46; INF: 166, 202
 Newman, J. E., DET: 78
 Newman, M. T., DET: 195
 Newman, R. W., DET: 177
 Newman, W., PRO: 96
 Nicholls, A. O., DIR: 112, 265
 Nichols, J. O., DET: 151
 Nicholson, S. E., PRO: 40, 157, 158
 Nickerson, E. C., GCC: 51, 53
 Nicolis, C., INF: 66
 Niehaus, F., GCC: 218, 221, 235, 240, 242, 262, 280
 Niiler, P. P., GCC: 84
 Nikolsky, V., INF: 202
 Nilsson, B., INF: 200
 Nilsson, T., GCC: 191, 195
 Noble, I. R., DET: 159
 Norby, R. J., GCC: 263; DIR: 14, 15, 188, 190, 192
 Nordhaus, W. D., GCC: 217, 218, 219, 221, 222, 223, 224, 227, 228, 229, 230, 233, 234, 237, 239, 240, 241, 243, 260, 261, 262, 268, 269, 272, 273, 276, 279, 280, 281, 283; INF: 164
 North, G. R., INF: 85, 161, 162, 177, 202, 212, 215, 313
 NRC Carbon Dioxide Assessment Committee, GLA: 7, 41
 NRC Climate Research Board, GLA: 41
 NRC Committee on Glaciology, GLA: 10, 40, 46, 65
 Nugent, R. P., DET: 184
 Nydal, R., GCC: 36
 Nye, J. F., PRO: 136; GLA: 265;
 Nye, P. H., GCC: 122
 Oates, W. E., DET: 38
 Oberbauer, S. F., DIR: 121
 O'Connell, C. P., DET: 110
 O'Connell, P. E., DET: 41
 Odum, E. P., DIR: 128
 Oechel, W. C., DIR: 14, 44, 120, 121, 124, 130, 134, 138, 141
 Oechsli, F. W., DET: 185, 187, 188
 Oerlemans, J., PRO: 115, 134, 135
 Oeschger, H., GCC: 10, 28, 29, 31, 33, 35, 36, 91, 98, 99, 100, 127, 130, 144, 146, 147, 148, 150, 152, 153, 154, 159, 218, 221, 222, 231, 241, 250, 253, 254, 255, 256, 257, 269, 270, 274, 277, 280, 282, 284; DIR: 42; PRO: 79, 115; INF: 158; GLA: 268
 Oetjen, R. A., PRO: 25
 Ogilvie, A. E. J., PRO: 64, 122
 Ogren, W. L., DIR: 58
 Ohring, G., INF: 50
 Okubo, T., DIR: 44
 O'Leary, J. W., DIR: 6
 Olesen, O. B., GLA: 159, 161, 162
 Oliver, R. C., PRO: 43, 46; INF: 163, 167, 219
 Olson, J. S., GCC: 6, 18, 116, 119, 120, 121, 123, 125, 128, 129, 143, 159, 177, 179, 180, 181, 186, 188, 189, 190, 198, 199, 200, 201, 202, 204, 205, 264, 266, 294, 300; DIR: 181; DET: 147
 Olson, P. R., DIR: 135
 Olson, W. P., DET: 193
 Olszyk, D. M., DIR: 23
 Ommundsen, A. M., GLA: 117, 123
 O'Neill, R. V., DIR: 45, 46, 47
 Oort, A. H., PRO: 26, 65, 68, 71, 72; INF: 40, 66, 115, 124, 157, 159, 161, 182, 198, 299
 Opdyke, N. D., INF: 250
 Orcut, G. H., DET: 47
 Orheim, O., PRO: 136; GLA: 125, 211, 214
 Orombelli, G., PRO: 136
 Orowan, E., GLA: 258
 Orwick, P. L., DIR: 44
 Osmond, C. B. O., DIR: 73, 120
 Osterkamp, T. E., PRO: 131, 133; GLA: 216
 Östlund, H. G., GCC: 93, 94
 Ostrem, G., GLA: 235
 Ottar, B., INF: 201
 Otto-Blienesner, B., INF: 242, 252
 Ou, S.-C., INF: 37, 157
 Overdieck, D., DIR: 134, 135, 140, 157, 165, 167
 Overgaard, S., GLA: 167
 Overpeck, J. T., DET: 158
 Ovington, J. D., GCC: 122
 Owen, T., INF: 240
 Owens, A. J., INF: 207, 217
 Özkaraynak, H., INF: 200
 Pacific Fishing Partnership, DET: 98
 Padgett, S. J., DET: 179, 180, 181, 182
 Paez, A., DIR: 6, 18, 71, 129, 130, 134, 147, 194, 195
 Painter, R. B., DET: 44
 Pal, U. R., DIR: 75
 Palecki, M., PRO: 130
 Pallas, J. E., Jr., DIR: 59, 74, 112, 126, 127, 228, 233, 244, 257
 Palm, C. A., GCC: 127
 Paltridge, G. W., PRO: 58, 59, 76, 99, 104; INF: 31, 49, 160
 Palutikof, J. P., DIR: 196; DET: 14, 162; PRO: 64; INF: 244, 245, 246
 Pan, Y. H., PRO: 68, 71, 72; INF: 182
 Pankrath, J., GCC: 120
 Panshin, A. J., DET: 147

Pant, G., PRO: 156
 Paolino, D. A., PRO: 41, 48
 Paren, J. G., GLA: 51, 118, 120, 123, 202
 Parent, J. D., GCC: 72, 73, 76, 77
 Parker, D. E., PRO: 41, 42, 57, 63, 65, 67, 68, 69, 70, 72, 73, 75, 82, 84, 99, 182; INF: 12
 Parkinson, C. L., PRO: 111, 114, 125, 127, 128; GLA: 50, 243, 326
 Parkinson, J. H., PRO: 47
 Parlange, J. Y., DIR: 59
 Parrish, R. H., DET: 100, 111, 115, 127
 Parsons, J. E., DIR: 19, 60
 Parsons, T. R., DET: 109
 Parthasarathy, B., PRO: 156
 Pastor, J. J., GCC: 122, 257, 277, 294
 Paterson, W. S. B., PRO: 135, 136; GLA: 145, 146, 149, 326
 Patterson, D. T., DIR: 6, 18, 67, 111, 113, 157, 158, 159, 160, 162, 163, 167, 224, 225, 226, 249, 250, 251, 253, 256, 257
 Patterson, E. M., INF: 201
 Payne, M. W., PRO: 131
 Pearcy, R. W., DIR: 5, 72, 73, 114, 123, 157, 161; DET: 28
 Pearman, G. I., GCC: 30, 37, 38, 44, 45, 53, 54, 55, 131, 132, 146, 148, 149, 165, 166, 167, 168, 251, 252, 254, 257, 268, 273, 275, 280; DIR: 3, 4, 59, 179
 Pease, C. H., PRO: 112
 Pecan, E. V., DIR: 3, 4
 Peedin, G. F., DIR: 145
 Peel, D. A., GLA: 198, 207
 Peet, M. M., DIR: 57, 111, 112, 245, 246, 250, 251, 253
 Peixoto, J. P., PRO: 26; INF: 66, 198
 Peltier, W. R., PRO: 96, 115; GLA: 83, 93, 94, 99, 101, 143
 Pendleton, D. F., DIR: 44
 Peng, T.-H., GCC: 9, 20, 29, 36, 37, 91, 92, 93, 96, 99, 103, 104, 127, 130, 146, 148, 150, 156, 157, 159, 160, 161, 169, 179, 192, 195, 250, 251, 252; INF: 180
 Penman, H. L., DIR: 55
 Penner, J. E., INF: 203
 Penning de Vries, F. W. T., DIR: 42, 55
 Penz, U., GLA: 220
 Perkin, R. J., GLA: 275, 277
 Perry, A. M., GCC: 79, 217, 228, 229, 230, 235, 237, 240, 242, 243, 268, 269, 270, 274, 278, 279, 280; DET: 158
 Perry, C. W., DIR: 25
 Perry, H., GCC: 217, 218, 232
 Perry, M. J., GCC: 97
 Pershagen, H., PRO: 117
 Persson, R., GCC: 123, 125
 Perutz, M. F., GLA: 258
 Peterman, R. M., DET: 110
 Peterson, B. J., GCC: 88, 96, 97
 Peterson, G. M., INF: 247
 Peterson, J. T., GCC: 38
 Peterson, K. M., DIR: 137, 138, 161, 162, 163, 167
 Peterson, L. C., GCC: 191
 Peterssen, S., DET: 42
 Pettersson, A., GCC: 122
 Pettit, K. G., DIR: 179
 Péttré, T. L., PRO: 130, 131, 132
 Peyton, T. O., INF: 199
 Pfister, C., PRO: 120
 Phene, C. J., DIR: 19, 60
 Philander, S. G., II, GCC: 51
 Phillips, D. A., DIR: 69, 75
 Phillips, N. A., INF: 70
 Pigott, J. P., GCC: 193
 Pilat, M. J., INF: 46
 Pilipowskij, S., INF: 38
 Pillsbury, R. D., GLA: 50, 119, 121, 123
 Pinkard, J. A., DIR: 70
 Pisias, N. G., GCC: 31, 34, 190, 195; INF: 240
 Pitcher, E. J., INF: 108, 344
 Pittock, A. B., PRO: 31, 47, 158; INF: 202, 241, 244
 Pivovarova, Z. I., PRO: 45, 46, 83
 Plass, G. N., INF: 37, 286, 288
 Platt, C. M. R., INF: 31, 49
 Platt, T., DET: 139
 Plochmann, R., GCC: 21; DET: 151, 161
 Plummer, L. N., GCC: 218, 231
 Pocklington, R., PRO: 100, 102, 103; GLA: 106, 107
 Podzimek, J., INF: 201
 Poisson, A., GCC: 90
 Pol, S. A., GLA: 292
 Polar Research Board, PRO: 172, 173; GLA: 10
 Poldervaart, A., GCC: 182
 Pollack, J. B., INF: 45, 46, 47, 168, 199, 200, 212
 Pollak, L. D., PRO: 32, 35
 Pollard, D., PRO: 115
 Pollard, W. H., PRO: 131
 Pollitzer, R., DET: 193
 Popenoe, H., GCC: 122
 Porch, W. M., INF: 201
 Porter, S. C., PRO: 136
 Posamentier, H. W., PRO: 135
 Posch, M., GCC: 265
 Posey, J., PRO: 119
 Post, W. M., GCC: 18, 117, 122, 181, 257, 277, 294
 Postel, S., DET: 34
 Potter, G. L., INF: 40, 167, 324, 325, 326, 333, 346
 Potter, J. R., DIR: 58; GLA: 51, 118, 120, 123, 201, 202
 Potter, K. W., DET: 30, 31, 41
 Potvin, C., DIR: 6, 122, 126, 127, 133
 Preisendorfer, R., PRO: 154
 Prell, W. L., GCC: 191, 195; INF: 247
 Prentice, I. C., INF: 247, 248
 Preobazhensky, Yu. V., PRO: 122
 President's Science Advisory Committee, DET: 4
 Price, N. B., GCC: 96
 Prindle, R. A., DET: 196
 Prioul, J. L., DIR: 46
 Privett, D. W., INF: 288
 Prodi, F., INF: 201
 Prospero, J. M., INF: 200
 Pruchniewicz, T. G., INF: 223
 Prudhomme, T. I., DIR: 14, 21, 22, 121, 134, 148
 Pruter, A. T., DET: 110
 Pulver, A. E., DET: 177
 Purnell, R. E., DET: 194
 Putnam, A. R., DIR: 192
 Quay, P. D., GCC: 29, 95, 152; PRO: 46
 Quayle, R., DET: 189
 Quayle, R. G., PRO: 154
 Quebedeaux, B., DIR: 252, 254, 255, 258
 Quenouille, M. H., PRO: 84
 Quinn, J. A., DIR: 4, 126, 138, 139, 199
 Quiroz, R. S., PRO: 73, 82, 84; INF: 202
 Raatz, W. E., INF: 201
 Radin, J. W., DIR: 113
 Radke, L. F., INF: 201
 Radok, U., PRO: 135; GLA: 26, 156
 Rahn, K. A., INF: 201
 Rainbird, A. F., PRO: 152
 Raiswell, R., GCC: 196
 Ralston, C. W., GCC: 120, 121, 125, 126; DET: 150
 Ramage, C. S., PRO: 33, 39, 121
 Ramanathan, K. S., DET: 176
 Ramanathan, V., PRO: 13, 21, 26, 77, 80, 81; INF: 34, 35, 36, 37, 40, 41, 42, 43, 48, 49, 50, 85, 87, 108, 153, 206, 207, 208, 209, 210, 215, 217, 222, 240, 289, 291, 292, 294, 295, 299, 302, 305, 323, 324, 325, 327, 328, 329, 331, 332, 333, 346
 Ramirez, J. M., DET: 4
 Rampino, M. R., GCC: 278; PRO: 42, 44
 Randall, G. W., DIR: 189, 190, 191
 Rango, A., PRO: 117
 Ran'kova, E. Ya., PRO: 38, 58, 59
 Raper, C. D., Jr., DIR: 44, 145
 Raper, S. C. B., PRO: 58, 59, 61, 62, 75, 76, 78, 127
 Raschke, K., DIR: 59, 112, 176
 Rasmussen, L. A., DET: 47; GLA: 52, 220, 235
 Rasmussen, R. A., GCC: 36, 188; INF: 194, 195, 196
 Rasmussen, E., PRO: 156, 158

Rasmussen, E. M., GCC: 191; INF: 40, 299
Rasool, S. I., INF: 46, 85, 212, 289, 346
Raven, P. H., GCC: 200
Raymond, C. F., GLA: 167
Raymont, J. E. G., GCC: 88
Raynaud, D., GCC: 28, 29, 35, 37
Reber, C. A., INF: 202
Rechsteiner, J., DET: 191
Reck, R. A., INF: 46, 87, 208, 209, 212, 292, 302, 305, 307, 308, 346
Record, R. G., DET: 177
Redfield, A. C., GCC: 88
Redmond, D. R., DET: 151
Reed, K. L., DIR: 46
Reed, R., PRO: 152
Reed, R. H., DIR: 187
Reed, R. K., DET: 108
Reeh, M., GLA: 156, 157, 162, 163, 167, 168, 233, 285, 288
Reeve, M. R., DET: 137
Regehr, D. L., DIR: 127, 141, 175, 177
Reich, P. B., DIR: 14
Reid, C. D., DIR: 138
Reid, G. C., INF: 202
Reid, J. L., GLA: 104, 130, 136
Reilly, J. M., GCC: 79, 219, 220, 221, 226, 227, 228, 230, 234, 236, 238, 240, 259, 292
Reiners, W. A., GCC: 119, 181
Reinsel, G. C., INF: 217, 218, 221
Reister, D. B., GCC: 219, 234, 237, 241, 260
Reitan, C. H., PRO: 31, 57
Remer, L. A., INF: 87, 292, 302, 311, 312, 313
Remsberg, E. E., INF: 47
Repin, R. O., PRO: 45
Revelle, R., GCC: 122, 127, 147, 182, 280; PRO: 40, 95, 151, 160; INF: 163, 195; GLA: 50, 94, 97, 98, 99, 100, 102, 124, 198, 233
Revelle, R. R., DIR: 197, 198; DET: 4, 5, 34, 119, 122
Reynaud, L., GLA: 222, 225, 252
Reynolds, J. F., DIR: 44, 101, 140
Richards, J. F., GCC: 121, 127, 129, 130, 296, 300
Richardson, L. F., INF: 14
Richey, J. E., GCC: 95
Richmond, K. A., DIR: 165
Riley, G. A., GCC: 180, 205
Rind, D., DIR: 196, 197; INF: 130
Riseborough, D. W., PRO: 133
Robb, W., DIR: 3, 130
Robbins, R. C., INF: 194, 201
Roberts, C. J., DET: 181
Robertson, J. D., GLA: 178
Robin, G. de Q., PRO: 134; GLA: 46, 123, 204

Robinson, A. R., INF: 178
Robinson, D., PRO: 117, 118
Robinson, E., INF: 201
Robinson, E. S., GLA: 210
Robinson, M., INF: 349
Robinson, M. A., DET: 99
Robinson, M. K., PRO: 100, 101, 102, 103
Robock, A., PRO: 31, 39, 43, 59, 82, 112, 113, 117, 136; INF: 15, 163, 166, 215
Rochard, C., DET: 181
Rochford, D. J., GLA: 116
Rodda, J. C., PRO: 40, 152
Rodgers, C. D., INF: 33, 34, 37, 215
Rodin, L. E., DET: 147
Roemmich, D., PRO: 100; INF: 182, 183; GLA: 110
Rogers, H. H., DIR: 14, 15, 16, 22, 26, 57, 59, 60, 62, 63, 67, 68, 69, 70, 71, 74, 78, 111, 112, 113, 130, 131, 157, 158, 179, 193, 194, 223, 225, 226, 227, 229, 249, 250, 252, 254, 255, 256, 257, 258, 259, 260
Rogers, J. C., PRO: 127
Rogner, H. H., GCC: 220, 233, 239
Rogot, E., DET: 179, 180, 181, 182, 183
Rohne, P. B., DET: 52
Ronov, A. B., GCC: 31, 192, 193, 194
Rooth, C., DET: 133
Ropelewski, C. F., PRO: 121, 123, 124, 125
Rose, D. J., GCC: 217, 219, 222, 228, 234, 236, 241, 243, 260, 278, 281
Rose, D. W., DET: 149
Rose, G., DET: 177, 181
Rose, K. E., GLA: 53, 178, 318, 320
Rosen, H. A., INF: 200, 201
Rosen, J. M., INF: 199
Rosenberg, N. J., GCC: 263; DIR: 66, 74, 133, 196; DET: 75, 79
Rosenthal, G. A., GCC: 200
Rosenwaike, I., DET: 178, 181, 183, 184
Rosenzweig, C., DIR: 197
Rossby, H. T., GCC: 84
Rotem, J., DET: 152
Rothschild, B. J., DET: 99, 133
Rotman, S. R., GLA: 198, 200
Rotty, R. M., GCC: 7, 11, 48, 65, 66, 67, 68, 70, 71, 75, 143, 218, 231, 232, 237, 250, 260, 262, 268, 280, 283; INF: 83
Rountree, B. H., DET: 79
Rouse, J. R., GLA: 200
Rovira, A. D., DIR: 132, 133
Rowe, J. S., DET: 153, 159, 160
Rowland, F. S., INF: 194, 195, 209
Rowntree, P. R., INF: 87, 99, 292, 295, 298, 299, 300, 302, 346
Royer, T. C., GLA: 143
Rubey, W. W., GCC: 181, 194
Ruddiman, W. F., INF: 247, 249
Ruderman, M. A., INF: 210
Rudolph, J., INF: 196
Rufy, T. W., Jr., DIR: 246
Rumbaugh, W. F., PRO: 34
Runeckles, V. C., DIR: 14
Runkle, J. R., DET: 150
Running, S. W., DET: 35
Russell, W. A., DET: 76
Rust, B. W., GCC: 37, 153, 154, 294; DIR: 45, 47
Ryan, P. B., INF: 43
Ryder, C., PRO: 123
Rylov, S. P., PRO: 118
Ryther, J. H., GCC: 89, 180; DET: 99, 109, 111
Sachs, H. M., INF: 247
Sacks, J. M., DIR: 46
Saeki, T., GCC: 190
Sagan, C., GCC: 262
St. Omer, L., DIR: 134, 140, 162
Sakamoto-Momiyama, M. (see Momiyama)
Saker, N. J., INF: 302
Salati, E., GCC: 262
Saldarriaga, J., GCC: 117, 126
Salinger, J. M., PRO: 31; INF: 241, 244
Salstein, D. A., INF: 198
Salt River Project, DET: 46, 50, 51, 52
Saltzman, B., INF: 70, 163
Sanchez, P. A., DIR: 75
Sandberg, P. A., GCC: 192
Sanderson, N., PRO: 153
Sanderson, T. J. O., GLA: 320
Sanford, R. L., GCC: 126, 257, 294
Sangster, G., DET: 193
Sapper, K., PRO: 42
Sarkisyan, A. S., GCC: 84
Sarmiento, J. L., GCC: 33, 36, 84, 91, 95, 100, 103, 104, 105, 146, 169, 192, 299; INF: 178, 179, 181, 240
Sarnthein, M., INF: 247
Sarofim, A. F., INF: 34
Sartz, R. S., GCC: 122
Sasamori, T., INF: 46
Sasek, T. W., DIR: 120, 121, 145
Sater, J. E., PRO: 126
Sauer, R. H., DIR: 44, 148
Saugier, B., DIR: 44
Saur, J. F. T., PRO: 32
Saxena, M. C., DIR: 75
Schaake, J., DET: 34
Schack, A., INF: 34
Schatten, K. H., INF: 202
Schelling, T. C., GCC: 266, 282; INF: 11
Scherler, K. E., GLA: 217, 219, 227
Schidlowski M., GCC: 194, 196
Schiff, H. I., INF: 209
Schlesinger, M. E., GCC: 266; DET: 15, 16, 17, 18; PRO: 65, 80, 81, 129, 165;

INF: 71, 87, 90, 91, 92, 93, 94, 95, 100, 104, 105, 106, 115, 116, 117, 130, 139, 144, 151, 155, 156, 158, 164, 172, 173, 175, 178, 179, 239, 242, 346, 348, 352, 353; GLA: 120, 261, 262, 267, 268, 269, 270, 271, 272

Schlesinger, W. H., GCC: 95, 118, 119, 120, 122, 126, 181, 195, 257, 277; DIR: 138, 181

Schmailzl, U., INF: 213

Schmidt, U., INF: 194

Schmidt, W. F., GLA: 280, 286, 287

Schmitt, J., DIR: 160

Schneider, S. H., GCC: 33, 195; DET: 71, 161; PRO: 31, 42, 47, 79, 82, 133; INF: 46, 49, 66, 85, 153, 154, 155, 158, 159, 161, 162, 163, 164, 166, 170, 171, 173, 175, 176, 177, 179, 182, 183, 186, 199, 212, 240, 243, 289, 294, 305, 323, 346, 348; GLA: 268

Schnell, R. C., GCC: 49, 132

Schroeder, E., GLA: 104, 106

Schroth, M. N., DIR: 192

Schüepp, M., PRO: 118

Schultze, C. L., DET: 37

Schuman, S. H., DET: 185, 187, 188

Schumm, S. A., DET: 44

Schumskiy, P. A., GLA: 166, 221

Schutz, C., INF: 120, 121, 126

Schwander, J., GCC: 28, 29

Schware, R., GCC: 242; INF: 247, 249

Schwarz, M., DIR: 76, 139

Schwarzkopf, M. D., INF: 33, 34

Scientific Committee on Ocean Research, GCC: 30, 56, 57, 296

Scott, N. A., INF: 33

Scotto, J., DET: 183

Scrimshaw, N. S., DET: 195

Sear, C. B., PRO: 31, 42, 84; INF: 199, 242

Seastedt, T. R., GCC: 181

Seckel, H., GLA: 27, 162, 164, 167

Seidel, S., GCC: 3, 11, 219, 227, 228, 230, 234, 241, 242, 260, 276, 278, 279, 280, 281; INF: 170, 174

Seiler, W., GCC: 120, 121, 124, 126, 177, 201; INF: 194, 195, 196

Seiver, D. A., DET: 176

Selby, J. E. A., INF: 34

Self, S., PRO: 42, 43, 44

Sellers, W. D., PRO: 113; INF: 47, 70, 85, 159, 161, 212, 215, 289, 313, 346

Sellman, P. V., PRO: 132

Selvin, S., DET: 184

Semtner, A. J., Jr., PRO: 115, 128, 129; INF: 242; GLA: 125

Senum, G. I., GCC: 179, 188

Serafino, G. N., INF: 38

Serson, H., GLA: 149

Sestak, Z., DIR: 17

Shaake, P., PRO: 31, 36

Shaal, L. A., PRO: 34

Shabecoff, P., INF: 170

Shackleton, N. J., GCC: 31, 33, 34, 55, 190; INF: 240, 241, 250

Shands, W. E., GCC: 4; DET: 149

Shantz, H. L., DET: 153

Sharkey, T. D., DIR: 17, 113, 120, 122, 126

Sharma, K. D., DET: 45

Sharpe, D. M., GCC: 117, 120, 125

Shaver, G. R., DIR: 134

Shaw, D., GLA: 104, 105

Shaw, G. E., INF: 201

Shawcroft, R. W., DIR: 78

Shearman, R. J., PRO: 40

Sheehy, J. E., DIR: 44

Sheehy, W., GLA: 174

Shepherd, J. G., DET: 105, 110

Shetter, J. D., INF: 194

Shettle, E. P., INF: 45, 46, 47, 200, 201

Shi, Y., GLA: 220, 221

Shibles, R., DIR: 70

Shimura, M., DET: 177

Shine, K. P., PRO: 128

Shinn, J. H., DIR: 14, 23, 26, 27, 63, 64, 111, 182

Shivashankar, K., DIR: 259

Sholkovitz, E. R., GCC: 96

Short, D. A., INF: 50

Shugart, H. H., GCC: 263, 266, 294; DIR: 38, 39, 44, 45; DET: 152, 158, 159, 161, 162

Shukla, J., PRO: 121; INF: 204, 216

Shumskiy, P. A., PRO: 131

Siccama, T. G., GCC: 266

Siddoway, F., DET: 80

Siegenthaler, U., GCC: 30, 33, 36, 99, 100, 101, 102, 103, 130, 146, 150, 151, 157, 179, 192, 218, 221, 222, 231, 241, 252, 253, 254, 255, 258, 269, 270, 271, 272, 277, 280; DIR: 42; PRO: 79; INF: 240; GLA: 268, 270

Sikonia, W. G., GLA: 265

Silsbury, J. H., DIR: 44

Simkin, T., PRO: 43, 44, 46

Simmons, D. A., GLA: 200

Simmons, S., DIR: 37

Simojoki, H., PRO: 130

Simon, J. P., DIR: 122, 123, 127

Simon, P. C., INF: 202, 203

Sinclair, J. B., DET: 84

Sinclair, T. R., DIR: 17, 18, 56, 57

Singh, H. B., INF: 196

Singh, V., PRO: 129, 152

Sionit, N., DIR: 6, 18, 67, 68, 70, 71, 72, 74, 111, 112, 113, 114, 127, 129, 130, 132, 133, 134, 139, 147, 160, 162, 175, 188, 192, 194, 195, 198, 224, 225, 226, 247, 249, 250, 252, 254, 255, 256, 259, 260, 264, 265, 266, 267, 268, 269, 270, 272; DET: 151

Sjoblom, V., DET: 113

Skjelvag, A. O., DIR: 39

Skogerboe, G. V., DET: 45

Skumanish, A., INF: 202

Slater, B. C. S., DET: 177

Slatis, H. M., DET: 184

Slatyer, R. O., DIR: 56, 230

Slotsvik, N., GLA: 120, 123

Slutz, R. J., PRO: 40, 48, 97

Smagorinsky, J., INF: 66, 70

Smirnov, V. I., PRO: 126

Smith, A. M., GLA: 204

Smith, D. D., DET: 44

Smith, E. A., PRO: 46, 47

Smith, G. L., INF: 299

Smith, H., DIR: 41

Smith, I. N., PRO: 115, 134, 136; INF: 73; GLA: 172, 173, 174, 222

Smith, L. P., DET: 52

Smith, M. W., PRO: 133

Smith, R. L., GCC: 191

Smith, S. D., DIR: 120, 121, 126, 127

Smith, S. V., GCC: 97, 180

Smith, W. H., DIR: 133

Smith, W. L., INF: 39

Snell, F. M., INF: 346

Soderlund, R., GCC: 97

Soil Conservation Service, DET: 83

Sollins, P., DIR: 44

Solomon, A. M., GCC: 189, 263, 264, 266, 267; DIR: 4, 141; DET: 5, 19, 56, 78, 80, 150, 151, 152, 153, 158, 159, 160, 161, 162, 163

Solomon, D. L., DIR: 36, 39, 41

Solomons, W., GCC: 97

Somerville, R. C. J., INF: 87, 292, 302, 311, 312, 313

Sonett, C. P., PRO: 46

Sorooshian, S., DET: 56

Southard, R. B., GLA: 237

Spalding, D. B., INF: 179

Sparhawk, W., GCC: 123

Speerschneider, C. I. H., PRO: 122

Spelman, M. J., INF: 104, 107, 144, 175, 176, 243, 314; GLA: 268

Sperling, W., PRO: 130

Spreiter, J. R., GCC: 268, 269, 270, 271, 272, 274, 277, 280

Spurr, S. H., DET: 152

Staley, J. M., DET: 151

Stamnes, K., INF: 201

Stamper, J. H., DIR: 39

Stanhill, G., GCC: 30, 37

Stansel, J., DET: 4

Stapper, M., DIR: 44

Starr, V. P., PRO: 68; INF: 198

Starr, W. L., INF: 221
 States, S. J., DET: 179
 Stauffer, B., GCC: 10, 28, 29, 31, 33, 35, 36, 282; PRO: 115; INF: 240; GLA: 10
 Steadman, R. G., DET: 189
 Steele, J. H., DET: 139
 Steinacker, R., PRO: 135
 Steinberg, M., GCC: 278
 Stenchikov, G. L., INF: 211, 212
 Stephens, G. L., INF: 49, 296, 306, 307, 308, 310
 Stephenson, S. N., GLA: 204
 Steponkus, P. L., DET: 151
 Steppuhn, H., PRO: 116
 Stern, J. T., Jr., DIR: 187
 Stewart, D. W., DIR: 77
 Stewart, R. W., DET: 5
 Stocking, M. A., DET: 44
 Stockton, C. W., DIR: 180; DET: 4, 34, 41, 50, 52, 61
 Stoeckenius, T., PRO: 156, 157, 159
 Stokes, G. M., GCC: 30, 36, 37
 Stolarski, R. S., INF: 209
 Stommel, H., GCC: 169; GLA: 104, 105, 106
 Stone, H. M., INF: 37
 Stone, P. H., INF: 87, 215, 292, 296, 297, 299, 302, 305, 313, 314, 315
 Stothers, R. B., PRO: 42, 44
 Stouffer, R. J., GCC: 265; DET: 74, 90, 153; PRO: 65, 72, 113, 114, 128, 129; INF: 74, 97, 98, 99, 100, 101, 102, 104, 105, 106, 107, 108, 124, 125, 133, 137, 138, 139, 140, 141, 142, 239, 243, 245, 249, 326, 327, 346
 Stove, G. C., GLA: 235
 Strahler, A. N., DET: 153
 Strain, B. R., GCC: 4, 264, 267; DIR: 3, 4, 5, 6, 37, 119, 120, 121, 122, 123, 126, 127, 129, 130, 139, 140, 141, 145, 157, 159, 160, 162, 188, 190, 194, 195, 199; DET: 4, 19, 25, 31, 55, 150, 151, 159, 160, 161, 173, 197
 Streete, J. L., INF: 201
 Streeter, S. S., INF: 247
 Street-Perrott, F. A., INF: 252
 Streten, N. A., PRO: 127
 Strickland, R. M., DET: 111, 128
 Strickler, R. F., INF: 30, 31, 37, 86, 290, 307, 308
 Strokina, L. A., PRO: 127
 Strubing, K., PRO: 126
 flumlaут over the u+
 Stuiver, M., GCC: 29, 32, 35, 36, 37, 130, 152, 159, 250, 251, 252, 295; DIR: 179; DET: 11; PRO: 46; INF: 240; GLA: 206, 280, 281, 320, 325
 Stumm, W., DET: 100, 102, 105
 Sturman, A. P., PRO: 124; GLA: 241
 Suess, H. E., GCC: 88, 89, 92, 93, 96, 147, 180; DET: 4
 Sullivan, W., INF: 163
 Sundquist, E. T., GCC: 11, 32, 34, 103, 177, 184, 190, 192, 204, 205, 218, 231
 Surano, K. A., DIR: 26, 27, 63, 64, 111
 Sutcliffe, W. H., DET: 108;
 Sutcliffe, W. H., Jr., GCC: 180
 Suter, J., PRO: 134, 136
 Suyetova, I. A., GLA: 172, 204, 210
 Svensson, B. H., GCC: 97
 Sverdrup, H. U., INF: 159
 Sverrisson, M., GLA: 225
 Swain, A. M., INF: 248, 249
 Swartzman, G. L., DIR: 42, 44
 Sweeney, D. G., DIR: 44
 Swift, J. H., GCC: 179, 199; PRO: 102; GLA: 133, 134, 135
 Swift, M. J., DET: 151
 Swithinbank, C. W. M., GLA: 185, 222, 234, 235, 237, 289, 292
 Symons, G. J., PRO: 42; INF: 199
 Syzdek, L., DET: 191
 Szaniawski, R. K., DIR: 67
 Sze, N. D., INF: 198, 207, 208
 Tabata, S., PRO: 32, 100, 103
 Tabler, R. D., PRO: 118
 Tabony, R. C., PRO: 31, 40, 152, 155, 156
 Tait, D. E. N., GCC: 179
 Takahashi, T., GCC: 19, 33, 84, 86, 87, 88, 90, 91, 93, 104, 167, 191, 192; DET: 100; INF: 240; GLA: 121
 Taljaard, J. J., INF: 10, 114, 116, 120, 126
 Tamm, C. O., GCC: 122
 Tanaka, I., DIR: 5, 222, 224, 237, 238, 241, 251
 Tanaka, K., GLA: 82
 Tanaka, M., GCC: 44; PRO: 130; INF: 46, 212
 Tangborn, W. V., DET: 47; GLA: 222
 Tanner, C. B., DIR: 56
 Tans, P. P., GCC: 130, 159
 Taylor, H. W., PRO: 125
 Tchernia, P., GLA: 121, 214
 Teare, I. D., DIR: 57
 Teltch, B., DET: 190
 Temkin, R. L., INF: 346
 Tenhunen, J. D., DIR: 46, 176
 Tharp, M. L., GCC: 189, 264; DET: 151, 158, 159, 161
 Theil, H., DET: 47
 Theilacker, G. H., DET: 110
 Thekaekara, M. P., INF: 202, 203
 Thesen, A., DIR: 39
 Thie, J., PRO: 132
 Thomas, J. F., DIR: 69, 70, 113
 Thomas, M. D., DIR: 60, 61
 Thomas, R. H., PRO: 135; GLA: 31, 52, 53, 55, 172, 174, 181, 182, 183, 184, 186, 188, 235, 280, 303, 317, 318, 319, 320, 321, 325, 326
 Thompson, C. R., DIR: 23
 Thompson, S. L., GCC: 33; DET: 161; INF: 154, 162, 164, 175, 176, 177, 243; GLA: 268
 Thorarinsson, S., PRO: 95; GLA: 75, 139
 Thorne, G. N., DIR: 6, 67, 68, 69, 70, 71, 73, 112, 113, 114, 218, 219, 220, 224
 Thorne, J. H., DIR: 113
 Thornley, J. H. M., DIR: 41
 Thorud, D. B., DET: 40, 53
 Tibbitts, T., DIR: 13
 Till, J. E., GCC: 153
 Timmis, R. J., GLA: 207
 Ting, I. P., GCC: 191
 Tissue, D., DIR: 120, 121, 122, 126, 127, 129, 132, 133, 134, 139, 140, 141, 145, 147
 Titus, J. G., PRO: 94
 Tjoa, W. S., DET: 176
 Todd, D. R., DET: 25
 Todini, E., DET: 56
 Toggweiler, J. R., GCC: 33, 36, 93, 103, 192; INF: 240
 Tolbert, N. E., DIR: 120, 123, 125, 128, 134
 Tolley, L. C., DIR: 6, 126, 127, 129, 130, 139, 141, 157, 159, 160, 162, 194, 195
 Tomlinson, J. H., GCC: 266
 Tont, S. A., DET: 99
 Toon, O. B., INF: 44, 45, 46, 200
 Torrey, E. F., DET: 177
 Tosi, J., GCC: 134
 Tosterud, R., DET: 71, 72
 Trabalka, J. R., GCC: 253, 267, 268, 270, 273, 274, 275, 276; DET: 4, 11, 12, 19, 151, 160, 173; PRO: 5, 165, 166; INF: 3, 18, 83, 157, 164, 169, 240
 Trabant, D. C., PRO: 136; GLA: 222, 246
 Tramoni, F., PRO: 130
 Tregunna, E. B., DIR: 263
 Trenberth, K. A., PRO: 41, 48
 Tressler, W. L., GLA: 117, 123
 Trijonis, J., INF: 200
 Trimble, G. R., GCC: 122, 257
 Tromp, S. W., DET: 177, 183, 192
 Trumbore, S., GLA: 121, 123
 Tsumura, K., GLA: 78
 Tubbs, L. D., INF: 35
 Tucker, C. J., GCC: 50, 51, 125, 295
 Tucker, G., PRO: 152
 Tucker, G. B., INF: 360
 Tucker, H. A., DET: 76
 Turco, R. P., INF: 167, 198, 199, 212
 Turner, J., DIR: 135

Turner, J. S., **GCC**: 84; **INF**: 159, 179

Twitty, J. T., **INF**: 200

Twomey, S., **INF**: 44

Tyndall, J., **DET**: 13

Uehara, G., **DIR**: 75

UNESCO/IASH, **PRO**: 111, 134

United Nations, **GCC**: 66, 67; **DET**: 37, 43

United Nations Educational, Scientific, and Cultural Organization, **GCC**: 181

United Nations Environment Programme, **DET**: 43

United Nations Food and Agriculture Organization, **DIR**: 103

United Nations Water Conference, **DET**: 34

United States Army Corps of Engineers, **DET**: 37

United States Bureau of the Census, **DET**: 72

United States Congress, Office of Technology Assessment, **DET**: 43

United States Congressional Budget Office, **DET**: 34

United States Department of Agriculture, **DET**: 73, 82, 147, 149, 152

United States Department of Commerce, **PRO**: 117

United States Department of Energy, **GCC**: 5, 17, 95, 96; **DIR**: 3, 4, 35; **DET**: 13, 56, 173, 197

United States Department of Health and Human Services, **DET**: 173

United States Energy Information Administration, **GCC**: 71

United States General Accounting Office, **DET**: 42

United States Water Resources Council, **DET**: 43

University of Oulu, **PRO**: 117

Unsworth, H. M., **DIR**: 23

Untersteiner, N., **PRO**: 111, 124, 129, 137

Ursin, E., **DET**: 113

Uttinger, H., **PRO**: 118, 120

Uyeda, S., **GLA**: 82

Valero, F. P. J., **INF**: 201

Valle, R., **DIR**: 17, 18, 20, 57, 60, 65, 69, 247

van Bavel, C. H. M., **DIR**: 13, 46, 243, 244

Van Bennekom, A. J., **GCC**: 97

Van Cleve, K., **DIR**: 137

Vanderbilt, C., **DET**: 98, 99

van de Hulst, H. C., **INF**: 29

van den Bosch, R., **DET**: 83

van der Veen, C. J., **PRO**: 115, 134

Van Keulen, H., **DIR**: 44

van Laar, H. H., **DIR**: 127, 222, 227

van Loon, H., **PRO**: 31, 41, 48, 61, 63

Van Ness, J. W., **DET**: 41

van Volkenburgh, E., **DIR**: 27

Varanasi, P., **INF**: 222

Vaux, H. J., **DET**: 34

Veizer, J., **GCC**: 194

Venkatachalam, P. S., **DET**: 176

Verhoeven, P., **GCC**: 197

Vernadsky, V. I., **GCC**: 205, 302

Verniani, F., **INF**: 159

Veronis, G., **GCC**: 169

Viecelli, J. A., **GCC**: 100, 146, 255, 296

Viereck, L. A., **DIR**: 138

Vierling, E., **DIR**: 77

Vigdorchik, M. E., **PRO**: 132

Vincente, R. O., **GLA**: 93

Vines, R. G., **PRO**: 154

Vinje, T. E., **PRO**: 126; **GLA**: 214

Vinnikov, K. Ya., **PRO**: 31, 38, 39, 57, 58, 59, 60, 61, 63, 64, 82, 83; **INF**: 151, 152, 163, 244

Vissiy, K., **INF**: 200, 201

Vlassak, K., **DIR**: 259

Voge, M., **DET**: 194

Vogel, J. C., **GCC**: 119

Volk, T., **GCC**: 105

Volz, F. E., **INF**: 201

von Caemmerer, S., **DIR**: 17, 46, 121

von Rudloff, H., **PRO**: 32

Vose, P. B., **GCC**: 262

Vowinkel, E., **PRO**: 126

Vtyurin, B. I., **PRO**: 131

Vu, C. V., **DIR**: 69

Wade, J. C., **DET**: 44, 45

Wadham, P., **PRO**: 124, 126

Wagener, K., **GCC**: 130

Waggoner, A. P., **INF**: 200

Waggoner, P. E., **DIR**: 75, 175, 197, 198; **DET**: 5, 34, 74, 75, 152; **PRO**: 40, 151, 160

Walker, D. A., **DIR**: 113, 121, 174

Walker, E. R., **PRO**: 124

Walker, G. T., **PRO**: 156, 158

Walker, J., **INF**: 87, 292, 295, 298, 299, 300, 302, 346

Walker, J. C. G., **INF**: 223

Walker, J. F., **DET**: 30

Walker, W. R., **DET**: 45

Wallace, J. M., **GCC**: 191

Wallén, C. C., **PRO**: 57; **GLA**: 232

Walsh, J., **INF**: 116, 349

Wallis, J. R., **DET**: 31, 41, 56, 58

Wallwork, J. A., **DET**: 151

Walsh, J. E., **PRO**: 111, 112, 113, 117, 121, 125, 126, 127, 154; **GLA**: 242, 243

Walsh, J. J., **GCC**: 9, 97; **DET**: 109, 127, 139

Walshaw, C. D., **INF**: 33, 37, 215

Walton, J. J., **INF**: 213

Walton, J. L. W., **GLA**: 202, 204, 309

Wang, W.-C., **GCC**: 242; **PRO**: 165; **INF**: 43, 87, 134, 205, 206, 207, 208, 209, 210, 212, 215, 217, 219, 220, 221, 222, 292, 296, 297, 300, 301, 302, 305, 307, 309, 310, 311, 312, 313, 314, 315

Wangersky, P. J., **GCC**: 96

Wann, M., **DIR**: 44

Wardlaw, I. F., **DIR**: 133

Waring, R. H., **GCC**: 199; **DIR**: 135

Warren, S. G., **PRO**: 116, 118; **INF**: 155, 161, 153

Washburn, A. L., **PRO**: 132

Washington, W. M., **GCC**: 34, 195; **DET**: 15, 25, 55; **PRO**: 79, 114, 128; **INF**: 90, 91, 92, 93, 94, 97, 100, 104, 105, 106, 108, 109–112, 114, 116, 117, 118, 120, 121, 122, 124, 127, 128, 130, 131, 132, 133, 134, 135, 140, 142, 144, 156, 213, 214, 240, 297, 346

Waterman, L. S., **GCC**: 30

Watson, R. A., **INF**: 250

Watson, R. L., **DIR**: 46

Watts, J. A., **GCC**: 17, 143, 181

Watts, R. D., **GLA**: 237

Watts, R. G., **INF**: 155, 179, 182, 183, 323

Waymire, E., **DET**: 59

Weare, B. C., **GCC**: 49; **PRO**: 68, 71, 156; **INF**: 346

Weatherly, A. H., **DET**: 99

Weaver, W. R., **INF**: 32

Webb, T., III, **GCC**: 266; **DET**: 151, 158, 159, 161; **PRO**: 6, 40, 64; **INF**: 247, 248, 249, 250, 251

Webb, W., **DIR**: 38, 39

Webster, F., **GCC**: 301

Webster, P. J., **INF**: 49, 306, 307, 308, 324

Weeks, W. F., **PRO**: 124

Weertman, J., **PRO**: 115; **GLA**: 46, 224, 280, 281, 285, 288, 289, 292, 293, 294, 306, 319

Wehrung, D. A., **DET**: 177

Weidick, A., **GLA**: 25, 155, 156, 159, 161, 162, 166

Weinberg, A. M., **INF**: 213

Weinman, J. A., **INF**: 49, 200

Weinstein, D. A., **DET**: 158

Weisbin, C. R., **INF**: 340

Weiss, H. V., **INF**: 201

Weiss, R. E., **INF**: 200

Weiss, R. F., **GCC**: 86, 90, 92, 94, 167, 258; **INF**: 196, 197

Weissert, H. J., **GCC**: 195

Welhan, J. A., **GCC**: 179, 203

Weller, G., **PRO**: 79, 120; **INF**: 151, 163; **GLA**: 222

Wellock, C. E., **DET**: 191

Wells, N. C., INF: 87, 164, 292, 300, 301, 302, 346; GLA: 268

Wells, W. C., INF: 201

Wenk, T., GCC: 36, 103, 179, 192; INF: 240

Went, F. W., DIR: 13

Wesley, M. L., DIR: 23

West, D. C., DIR: 45, 141; DET: 152, 153, 158, 159, 160, 161, 162

West, R. R., DET: 179, 181

West, S. H., DIR: 58

Wetherald, R. T., GCC: 3; DIR: 196; DET: 15, 25, 30, 55, 74, 81, 90; PRO: 114; INF: 36, 49, 70, 86, 87, 90, 91, 92, 93, 94, 95, 96, 97, 100, 103, 104, 105, 106, 107, 108, 109–112, 114, 119, 121, 122, 124, 125, 126, 127, 128, 130, 131, 132, 133, 134, 135, 136, 140, 141, 142, 176, 206, 208, 215, 242, 249, 291, 292, 295, 296, 297, 298, 299, 302, 305, 307, 308, 309, 310, 315, 329, 330, 332, 333, 346, 350; GLA: 280

Wetzel, R. G., DIR: 165; DET: 103

Wexler, H., PRO: 95; GLA: 75, 123

Whillans, I. M., GLA: 167, 172

Whitby, K. T., INF: 200

White, M. R., GCC: 4; DIR: 6 PRO: 165

White, W., PRO: 95

White, W. H., INF: 200

Whitehead, J. A., Jr., GCC: 84

Whitfield, M., GCC: 205

Whittaker, R. H., GCC: 97, 115, 116, 119, 121, 123, 126, 128, 132, 180; DIR: 128, 173; DET: 147

Wiegert, R. J., DIR: 37

Wiese, W., PRO: 126

Wiesnet, D. R., PRO: 115, 117

Wigley, G., DIR: 59

Wigley, T. M. L., GCC: 30, 36; DIR: 197; DET: 13, 162; PRO: 6, 31, 40, 45, 57, 64, 74, 77, 79, 80, 81, 84, 123, 155, 159; INF: 12, 21, 59, 151, 158, 164, 171, 173, 178, 179, 222, 239, 240, 241, 242, 243, 244; GLA: 267, 269, 270

Wild, H., PRO: 38, 40

Wilkerson, G. G., DIR: 44

Willett, H. C., PRO: 33, 57; INF: 202

Williams, D. F., GCC: 191

Williams, G. P., PRO: 130

Williams, J., GCC: 218, 221, 235, 240, 243, 262, 280; PRO: 31, 41, 48, 61, 63, 64, 112, 114, 154; INF: 213, 241, 242, 243, 244

Williams, L. D., PRO: 6, 120; INF: 241

Williams, L. E., DIR: 113, 191, 248, 252, 254

Williams, M. A., DET: 44

Williams, P. M., GCC: 96

Williams, R. H., GCC: 217, 219, 221, 228, 229, 230, 235, 243

Williams, R. S., Jr., GLA: 226, 233, 234, 235, 237

Willson, R. C., PRO: 46, 47; INF: 166, 167

Wilson, C. A., INF: 99, 100, 136

Wilson, M. F., PRO: 115

Winchester, J., INF: 200

Wine, P. H., INF: 198, 199

Winestock, L., DIR: 23

Wing, L., PRO: 130

Wingenroth, J. L., GCC: 72

Winkler, P., INF: 200

Wischmeier, W. H., DET: 44

Wise, J. A., DET: 52

Witkamp, M., GCC: 122

Wittenbach, V. A., DIR: 58

Wittwer, S. H., DIR: 3, 5, 14, 61, 71, 130, 157, 191, 193, 196; DET: 25, 75

Wofsy, S. C., INF: 208, 210

Wolf, L., DIR: 44

Wolfe, J. A., GCC: 200

Wolff, G. T., INF: 200

Wollast, R., GCC: 96

Wong, S. C., GCC: 37, 44, 54, 120, 124; DIR: 6, 42, 59, 60, 69, 75, 78, 111, 113, 123, 129, 176, 178, 179, 223, 225, 228, 230, 231, 232, 233

Woo, M. K., GLA: 147

Wood, T. G., INF: 195

Woodcock, A. H., INF: 201

Woodman, J. N., DET: 149

Woodruff, N. P., DET: 80

Woodruff, S. D., PRO: 39, 40, 58, 59, 65, 76, 99, 104; INF: 160

Woodwell, G. M., GCC: 97, 119, 120, 121, 125, 126, 129, 130, 131, 132, 143, 159, 262, 263, 268, 295; DIR: 3, 4

Wooster, W. S., DET: 110, 113, 133

Wordie, J. M., GLA: 121

World Climate Research Programme, DET: 60; PRO: 179

World Energy Conference, GCC: 73, 75, 76, 77

World Health Organization, DET: 179

World Meteorological Organization, GCC: 18, 27, 30, 32, 36, 37, 251; DET: 12, 56, 196; PRO: 3, 6, 9, 22, 35, 45, 47, 79, 122, 137, 157, 179; INF: 4, 37, 39, 45, 50, 83, 193, 196, 197, 198, 199, 200, 207, 209, 211, 212, 223

Worsley, T. R., GCC: 192, 194

Worthington, L. V., GCC: 84; PRO: 100

Wright, H. E., Jr., INF: 250

Wright, R. D., DIR: 6, 175, 177, 198, 216

Wroblewski, J. S., DET: 139

Wu, P., GLA: 99

Wuebbles, D. J., GCC: 242, 283; PRO: 24; INF: 164, 165, 174, 195, 197, 198, 203, 207, 209, 210, 217, 218, 221, 222

Wulff, R. D., DIR: 121, 122, 129, 130, 131, 139, 145, 160

Wunsch, C., GCC: 84, 95, 301; PRO: 100; INF: 179, 182, 183; GLA: 106, 110

Wyndham, C. H., DET: 188

Wynne, B., GCC: 239

Wyrki, K., GCC: 92, 98

Xie, Z., GLA: 225

Yaalon, D. H., GCC: 118, 181

Yabuki, K., DIR: 57, 58, 160

Yamamoto, G., INF: 46, 212

Yamamoto, R., PRO: 31, 36, 38, 57, 58, 59, 61

Yang, S.-K., INF: 299

Yaron, D., DET: 46

Yasa, Z., INF: 200

Yevjevich, V. M., DET: 41

Yoder, C. F., GLA: 143

Yohe, G. W., GCC: 217, 219, 221, 223, 224, 227, 228, 234, 240, 241, 243, 260, 261, 262, 268, 269, 272, 273, 276, 279, 280, 281, 283; INF: 164

Yoshida, S., DIR: 70, 71, 238, 239, 240, 241, 242

Yoshino, M. M., PRO: 130

Yoshioka, G. A., DET: 153

Youji, D., PRO: 45

Young, N. W., GLA: 172, 173

Yumi, S., GLA: 93

Yurganov, L. N., INF: 196

Zakharov, V. F., PRO: 123, 124, 125, 127

Zangerl, A. R., DIR: 131, 163, 164, 165, 167, 169

Zelitch, I., GCC: 190, 201; DIR: 66, 120, 123, 125, 128, 134

Zeroni, M., DIR: 76

Zhakharov, V. F., GLA: 38

Zienkiewicz, O. C., GLA: 287

Zimmerman, F. W., DIR: 25

Zimmerman, P. R., GCC: 188; INF: 195, 196

Zinke, P. J., GCC: 18, 117, 118, 122, 143, 181

Zon, R., GCC: 123; DET: 153

Zotikov, I. A., GLA: 123

Zubenok, I. I., PRO: 127, 128

Zuber, M. S., DET: 76

Zumberge, J. H., GLA: 185, 186, 289, 292

Zumbühl, H. J., GLA: 224

Zwally, H. J., GCC: 258; PRO: 111, 124, 125, 127, 134; INF: 151, 152; GLA: 118, 125, 207, 235, 237, 242, 243

SUBJECT INDEX

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
17th International Horticultural Congress	-----	-----	-----	3	-----	-----
1982 International Conference on the Response of Plants ...	-----	-----	-----	3-4	-----	-----
24th Brookhaven Symposium on Biology	-----	-----	-----	3	-----	-----

A

Abiotic effects	-----	-----	-----	-----	100, 101, 124, 125	-----
Abiotic properties	-----	-----	-----	-----	129	-----
Ablation (glacial)	-----	-----	-----	-----	-----	42, 143, 155, 156, 161, 207, 281
measurement of patterns of	-----	-----	-----	-----	-----	26, 142, 255
Ablation fluxes (glacial)	-----	-----	-----	-----	-----	266
Ablation rate studies (glacial)	-----	-----	-----	-----	-----	158
Ablation rates (glacial)	-----	-----	-----	-----	-----	60, 147, 159, 262, 263, 264, 281
Ablation zones (glacial)	-----	-----	-----	-----	-----	43-44, 67, 150, 160, 255, 260, 265
Abscisic acid	-----	-----	-----	112	-----	-----
Abscission of leaves and fruits	-----	-----	-----	70	-----	-----
Abscission of plant organs	-----	-----	-----	70, 128	-----	-----
Absorption bands of carbon dioxide	-----	29, 30	-----	-----	-----	-----
Absorption coefficients	-----	45	-----	-----	-----	-----
Accidental deaths: seasonal variation in	-----	-----	-----	-----	184	-----

Acclimation

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Acclimation	-----	-----	-----	-----	xviii, 176, 188-189, 198-199, 201, 221 209	-----
definition	-----	-----	-----	-----	-----	-----
Acclimation to carbon dioxide concentration	-----	-----	-----	120, 187, 207	-----	-----
Accumulation (glacial)	-----	-----	-----	-----	-----	42, 43, 44, 140, 142, 143, 155, 172-173, 184, 198, 199, 207, 246, 250, 303, 305, 311, 314
distribution of measurement of net Antarctic patterns of	-----	-----	-----	-----	174	-----
-----	-----	-----	-----	-----	26, 28, 43, 255	-----
-----	-----	-----	-----	-----	210	-----
-----	-----	-----	-----	-----	210, 266	-----
Accumulation fluxes (glacial)	-----	-----	-----	-----	-----	262
Accumulation of carbon in plants and soil	-----	-----	-----	134, 136, 181	-----	-----
Accumulation profiles (glacial)	-----	-----	-----	-----	-----	43, 256
Accumulation rates (glacial)	-----	-----	-----	-----	-----	60, 156, 168, 260, 261, 262, 264, 296, 317, 321
Accumulation zones (glacial)	-----	-----	-----	-----	-----	150, 265
Acetate synthesis	-----	-----	-----	134	-----	-----
Acid rain	266	198	-----	-----	157, 159, 165	-----
Acidification of lakes	-----	-----	-----	-----	32	-----
Actinometric index	-----	-----	45	-----	-----	-----
Action initiation time	230	-----	-----	-----	-----	-----
Active cavity radiometer	-----	166, 167	-----	-----	-----	-----
Adaptation	-----	-----	-----	-----	13	-----
agricultural	-----	-----	-----	xxiv, 188	-----	-----
definition	-----	-----	-----	187	209	-----
forest	-----	-----	-----	119, 198	-----	-----
genetic	-----	-----	-----	xxii, 200	-----	-----
nutrient deficiency	-----	-----	-----	166	-----	-----
Adaptation to climate change	-----	-----	-----	-----	xix, 176, 177, 221	-----
agricultural	-----	-----	-----	-----	5, 74, 85-91, 195	-----
Adiabatic warming:	-----	-----	-----	-----	-----	-----
definition	-----	9	-----	-----	-----	-----
Advanced very high resolution radiometry	125	-----	-----	-----	-----	-----
Advection	84, 91	-----	-----	-----	-----	303, 305, 306
definition	-----	63	-----	-----	-----	-----
oceanic	-----	-----	-----	-----	123, 131, 135	-----
Advectional flow	146, 155, 157	-----	-----	-----	-----	-----
Aerial environment	-----	-----	-----	82	-----	-----
Aerial photography	-----	-----	-----	-----	-----	25, 147-149, 168, 233, 235

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Aerosols (see also Volcanic aerosols)	135	262, 211-213	4, 43, 165, 169	-----	-----	-----
anthropogenic atmospheric	-----	169, 221 193, 211, 221, 225, 279	-----	-----	-----	-----
atmospheric opacity of concentrations of	-----	167	-----	-----	-----	-----
cooling of planet by	-----	-----	183	-----	-----	-----
critical ratio of absorption to backscatter of	-----	47, 168, 193, 199	-----	-----	-----	-----
effects on climate of	-----	46	-----	-----	-----	-----
effects on clouds of	-----	46, 193, 223 44	-----	-----	-----	-----
effects on Earth's radiation budget of	-----	47-48	-----	-----	-----	-----
effects on planetary albedo of	-----	44, 46	-----	-----	-----	-----
effects on radiation of	-----	38, 44-48	-----	-----	-----	-----
effects on temperatures of optical properties	-----	168-169, 211, 212	-----	-----	-----	-----
radiative effects of	-----	45, 221, 224	-----	-----	-----	-----
radiative properties of	-----	44-48 45, 46, 48, 211, 262	-----	-----	-----	-----
scattering of sunlight by size distribution of	-----	47	-----	-----	-----	-----
spatial variation in composition of stratospheric	-----	44, 45 46	-----	-----	-----	-----
temporal variation in composition of tropospheric	-----	46, 47, 167, 193, 198, 199, 221	-----	-----	-----	-----
types of	-----	47, 167, 193, 199, 221 44, 200, 201	-----	-----	-----	-----
Afforestation	163	-----	-----	180	-----	-----
Africa	71	128, 132, 248, 249, 252	157-158, 160	-----	42, 147	-----
Afro-Asian Drought of 1972-73	-----	-----	-----	-----	42	-----
Agassiz Ice Cap	-----	-----	-----	-----	-----	147, 150
Agribusiness	-----	-----	-----	-----	73	-----
Agricultural activity	-----	-----	45	-----	-----	-----
Agricultural adaptation	-----	-----	-----	xxiv, 188	-----	-----
Agricultural chemicals	-----	-----	-----	-----	90	-----
Agricultural Cooperative Extension Service	-----	-----	-----	-----	73	-----
Agricultural development	-----	217	-----	-----	-----	-----
Agricultural drainage	-----	-----	-----	-----	83	-----
Agricultural economy	-----	-----	7	-----	-----	-----
Agricultural ecosystems	-----	-----	-----	210	-----	-----
Agricultural infrastructures	-----	-----	-----	-----	71, 73	-----
Agricultural lands: abandonment of new	164	-----	-----	-----	83	-----

Agricultural practices

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Agricultural practices	-----	-----	-----	xxv, 46, 137, 187	72, 80, 81-82, 83, 84, 87	-----
Agricultural production efficiency	-----	-----	-----	-----	72, 74	-----
Agricultural research and education: state and federal	-----	-----	-----	-----	73	-----
Agricultural Research Service	-----	-----	-----	-----	91	-----
Agricultural systems	-----	-----	-----	-----	18	-----
Agricultural technologies	-----	-----	-----	13	72	-----
Agriculture	96, 127, 198	xxii, 3, 62, 279	-----	-----	xv, xvii, 6, 69-93, 195, 212-218, 219, 221	-----
dry land (see also Dryness belt):	-----	-----	-----	-----	81	-----
expansion of strategies for eastern U.S.	-----	-----	-----	198	81	-----
economic stresses on institutional support for irrigated rainfed	-----	-----	-----	-----	xviii, 71	-----
use of fossil fuels in water availability and western U.S.	-----	-----	-----	73	45, 81	-----
-----	-----	-----	-----	-----	81-82	-----
-----	-----	-----	-----	-----	72	-----
-----	-----	-----	-----	198, 200	81	-----
Agronomic selection	-----	-----	-----	200	-----	-----
Agung	48	44, 199, 213	43, 68, 73, 84	-----	-----	-----
Air conditioning	-----	-----	-----	-----	176, 188, 199, 216	-----
Air movement	-----	-----	-----	xviii, 13, 81	-----	-----
Air pollution	-----	-----	-----	-----	157, 159, 165, 196, 200, 214	-----
effects of effects on plants of	263, 266	-----	-----	xix, xxv, 14, 18, 83, 87, 89, 188, 209	-----	-----
Air-sea interactions	-----	-----	-----	-----	-----	114
Air-sea interface	-----	-----	-----	-----	113	-----
Air-sea temperature differences	-----	-----	74-77, 98, 99-100, 182	-----	-----	-----
Air-surface heat exchange	-----	161	-----	-----	-----	-----
Air temperature (see also Temperature)	-----	-----	-----	-----	43, 314	-----
analyses of antarctic data on record of	-----	-----	98	-----	-----	-----
-----	-----	-----	62, 75	-----	-----	-----
-----	-----	-----	39	-----	-----	-----
-----	-----	-----	xix	-----	-----	-----
Air temperature during snowfall	-----	-----	-----	-----	-----	150
Airborne fraction	55, 57, 99, 100, 102, 152, 154, 155, 224, 254,	164	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Airborne fraction (continued)	255, 256, 267, 269, 270, 277, 280	-----	-----	-----	-----	-----
Airborne materials related to human health	-----	-----	-----	-----	190-192, 199, 212	-----
Aircraft emissions	-----	197, 210, 218, 219, 223	-----	-----	-----	-----
Aircraft measurements	43-46	-----	-----	-----	-----	-----
Alaska: coastal waters of snow and ice in	-----	-----	120, 127, 131-132, 133, 136	-----	111	-----
Alaska Current	-----	-----	-----	-----	112	-----
Alaska Range	-----	-----	-----	-----	-----	141, 223, 246
Albedo	-----	7, 61, 86, 167, 211, 271, 290	112, 113, 114, 117, 118, 169	-----	-----	314
aerosol induced changes in definition	-----	46, 47	-----	-----	-----	-----
earth's	297	-----	111-112	-----	-----	-----
effect of clouds on	-----	-----	112, 167, 175	-----	102, 162	-----
feedbacks of	-----	306, 310, 311 xxv, 154, 155, 162, 306, 310, 311, 358	----- 134	-----	-----	-----
increased Antarctic integrated spectral regional change values of	-----	-----	118	-----	-----	204
-----	-----	193	-----	-----	-----	-----
-----	-----	-----	112	-----	-----	-----
Albedo feedback processes	-----	-----	21	-----	-----	-----
Aletsch Glacier	-----	-----	-----	-----	-----	217, 224
Aleutian Basin	-----	-----	-----	-----	106, 112	-----
Alfalfa weevil	-----	-----	-----	-----	84	-----
Alfalfa	-----	-----	-----	61, 75, 103, 105-109, 216-217	75-77	-----
Alfisols	-----	-----	-----	-----	80	-----
Algal production	97	-----	-----	-----	-----	-----
Alkalinity: oceanic	33, 88, 91, 95, 102, 105, 106, 152, 168, 169	-----	-----	-----	-----	-----
Allelopathy	-----	-----	-----	133, 192	-----	-----
Allergens: airborne human	-----	-----	-----	-----	190-192 199	-----
Alps, The	-----	-----	133, 136	-----	-----	42, 60, 141, 223, 224, 226, 227
Alternative energy forms	77, 282	-----	-----	-----	-----	-----
Alternative energy system costs	77	-----	-----	-----	-----	-----
Altithermal definition	-----	250 18	-----	-----	-----	-----

Altitude

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Altitude:						
effect on warming of	-----	-----	-----	-----	-----	48, 62
Aluvial flood plains	-----	-----	-----	-----	82	-----
Aluvial groundwater systems	-----	-----	-----	-----	37	-----
Alvarez asteroid-impact hypothesis	-----	168	-----	-----	-----	-----
Amazon Basin	-----	132	38	-----	-----	-----
Ambrosia	-----	-----	-----	131, 158	-----	-----
American Society for Testing Materials	72	-----	-----	-----	-----	-----
Amery Ice Shelf	-----	-----	-----	-----	-----	28, 172, 198, 284-286, 301, 302
Ammonia	293	-----	-----	-----	-----	-----
Amundsen-Bellingshausen coastline	-----	-----	-----	-----	-----	120, 124
Amundsen Sea	-----	-----	-----	-----	-----	5, 29, 31, 48
Anaerobic decay	188, 198	-----	-----	-----	-----	-----
Analog data	-----	241	-----	-----	-----	-----
Analog years: methods for choosing	-----	244	-----	-----	-----	-----
Analogs	-----	17	-----	-----	-----	-----
Anatomy	-----	-----	-----	102	-----	-----
Anchovy	-----	-----	-----	-----	110, 113, 127	-----
Andes, The	-----	-----	127, 131	-----	-----	23, 67, 143
Animal diversity	-----	-----	-----	134	-----	-----
Animal migrations	-----	-----	-----	-----	118	-----
Animal populations	-----	195	-----	-----	-----	-----
Animals: agricultural	-----	-----	-----	-----	72, 76, 78, 79, 80, 81, 84, 214, 215, 216, 217	-----
climatic risks to conception rates of	-----	-----	-----	-----	75	-----
effects of cold and heat stress on weight of	-----	-----	-----	-----	86	-----
mortality of	-----	-----	-----	-----	86	-----
physiology of	-----	-----	-----	-----	75, 212	-----
productivity of	-----	-----	-----	-----	86	-----
reproductive stress on	-----	-----	-----	-----	75, 212	-----
reproductive stress on	-----	-----	-----	-----	118	-----
Antarctic bottom water	-----	-----	-----	-----	-----	197
Antarctic catchment areas: accumulation over	-----	-----	-----	-----	-----	199, 297
Antarctic Circumpolar Current	83	-----	-----	-----	-----	47
Antarctic Convergence	-----	-----	-----	-----	-----	214
Antarctic drainage basins characteristics of	-----	-----	-----	-----	-----	56, 304
	-----	-----	-----	-----	-----	199

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Antarctic environment:						
simulation of	-----	-----	-----	-----	-----	65
Antarctic ice	-----	8, 73, 163	-----	-----	-----	-----
Antarctic Ice Sheet	-----	-----	132, 133, 134	-----	-----	1, 2, 3, 5, 7, 8, 60-61, 62, 63-64, 98, 174
influx over mass balance of	-----	-----	-----	-----	-----	176
	-----	-----	-----	-----	-----	12, 21, 61, 172-176
Antarctic Ocean	152, 169	-----	-----	-----	127	-----
Antarctic Peninsula	-----	-----	-----	-----	-----	31-33, 199, 204-206, 207
retreat of the ice margin of	-----	-----	-----	-----	-----	204
Antarctic temperatures:						
surface air warming trend in	-----	-----	62, 75	-----	-----	-----
	-----	-----	127	-----	-----	-----
Antarctica	32, 33, 44, 56	61, 92, 129, 130, 152	38, 61, 111-112, 119, 121, 123, 124, 131, 173	-----	11, 109	1, 28-34, 37, 46-58, 63, 66, 172-176, 197-208, 302
climate regimes of continental shelf of	-----	-----	-----	-----	-----	197
warm intrusions onto the	-----	-----	-----	-----	-----	117, 120, 122
isohydropleths for	-----	-----	-----	-----	-----	120, 124
mass balance of	-----	-----	-----	-----	-----	200
subglacial topography of	-----	-----	133, 135	-----	-----	28-30, 68, 97, 197-209, 210-215
Antarctica as a carbon dioxide sink	-----	-----	-----	-----	-----	121
Anthesis	-----	-----	-----	68, 71	-----	-----
Anthropogenic emissions	-----	30, 168	-----	-----	-----	-----
Anthropogenic factors affecting climates	143	-----	-----	-----	-----	-----
Anticyclonic motions	84	-----	-----	-----	-----	-----
Antitranspirants	-----	-----	-----	-----	83	-----
Aphids	-----	-----	-----	140	-----	-----
Aquaculture	-----	-----	-----	-----	99	-----
Aquatic life	-----	-----	-----	-----	44	-----
Aquatic plants	-----	-----	-----	-----	xiv, 19, 39, 44, 55, 59, 217	-----
Aquatic systems	-----	-----	-----	165	-----	-----
Aquifer depletion	-----	-----	-----	-----	82	-----
Aquifer recharge	-----	-----	-----	-----	36, 59, 82	-----
Aquifers:						
saltwater intrusion into	-----	-----	-----	-----	36	-----
Arabian Peninsula	-----	129, 132	-----	-----	-----	-----
Arabian Sea	-----	38	-----	-----	-----	-----
Arable land surface:						
extension of	-----	-----	-----	209	-----	-----

Aragonite

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Aragonite (see also Coral)	87-88, 92	-----	-----	-----	105	-----
Archean age	205	-----	-----	-----	-----	-----
Architectural changes and climate	-----	-----	-----	-----	173, 174, 175, 196, 200, 201-202, 216, 221	-----
Archival records of natural events	-----	-----	181	-----	-----	-----
Arctic surface air temperatures of	-----	92, 241, 247	114, 123, 129	141	-----	-----
	-----	-----	60-61, 75	-----	-----	-----
Arctic Basin	-----	-----	128	-----	-----	-----
Arctic ecosystems	-----	-----	-----	21, 120, 130, 137, 211	-----	-----
current carbon content of	-----	-----	-----	137, 142	-----	-----
Arctic haze	-----	44, 201	-----	-----	-----	-----
Arctic ice: fluctuations of	-----	-----	-----	-----	-----	243
Arctic Ocean sea ice changes in	-----	152	121, 124	-----	106	275
	-----	-----	-----	-----	-----	38, 245
Arctic plants	-----	-----	-----	124, 126, 131	-----	-----
Arctic sea ice: stability of summer extent of	-----	-----	137	-----	-----	-----
	-----	-----	127, 173	-----	-----	-----
Areal extent and distribution of ecosystems	162, 170-171	-----	-----	-----	-----	-----
Argentina	-----	129	-----	-----	127	-----
Argon-39	91, 105	-----	-----	-----	-----	-----
Argonne National Laboratory	-----	-----	-----	14, 24, 25	-----	-----
Arid regions	11	-----	-----	xxii, 126, 139, 147-148, 197, 201	30, 37, 38, 39, 60-61, 81, 83	-----
Arizona Groundwater Management Act	-----	-----	-----	-----	52	-----
Arizona soils	118	-----	-----	-----	-----	-----
Artificial lighting	-----	-----	-----	55	-----	-----
ARTUS	-----	-----	-----	43, 141, 142, 143, 148	-----	-----
Aruba	-----	-----	-----	-----	162	-----
Ash	-----	-----	-----	162	-----	-----
Asia land use in	71	130, 132	135	-----	34, 42, 45	2, 23, 60, 143
	129	-----	-----	-----	-----	-----
Aspen	-----	-----	-----	175, 178	-----	-----
Assimilation rates	-----	-----	-----	161	-----	-----
Asteroid impacts	200, 205	167, 168	-----	-----	-----	-----
Asthma: effects of weather on	-----	-----	-----	-----	178, 183, 192, 199, 215	-----
Atlantic Ocean	52, 91, 93-94, 101, 148, 152, 169, 257, 296	38, 247, 249	103, 157	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Atmosphere	5-7, 145-146, 180, 204, 291, 298, 300	60, 267	-----	-----	v, 3, 11, 74, 97, 190, 196	-----
absorption of solar radiation by	-----	29, 167	-----	-----	-----	-----
changes in the composition of the	-----	28-31	-----	-----	-----	-----
chemical processes in the circulation of	-----	205	-----	-----	-----	-----
shifts in	-----	-----	96, 171	-----	-----	-----
constituents of the	-----	-----	166	-----	-----	-----
convective mixing of	-----	3, 28-31, 262	-----	-----	-----	-----
definition	-----	264	-----	-----	-----	-----
dissipation of the kinetic energy of the	-----	60	-----	-----	-----	-----
global annual mean energy balance	-----	63	-----	-----	-----	-----
heat balance of the	-----	41, 326	-----	-----	-----	-----
heat capacity of	-----	199, 208	-----	-----	-----	-----
incomplete understanding of the chemistry of the	-----	6	-----	-----	-----	-----
interaction with the oceans of	-----	222	-----	-----	-----	-----
moisture content of	-----	11	-----	-----	-----	-----
nuclear tests in the	-----	-----	-----	-----	-----	-----
opacity of the	-----	98, 262	-----	-----	-----	-----
primitive equations of the	-----	210, 217, 221	-----	-----	-----	-----
projections of	-----	-----	-----	-----	-----	-----
radiation budget of the	-----	27, 39, 199, 205	-----	-----	-----	-----
radiative properties of	-----	66	-----	-----	-----	-----
radiative properties of gases in	-----	-----	-----	-----	-----	3, 49, 62, 267
records of	295	-----	-----	-----	-----	-----
seasonal changes in circulation of the	-----	60, 73, 265	-----	-----	-----	-----
stability of the	-----	44	-----	-----	-----	-----
stratification of lower surface pressure pattern of	-----	95	-----	-----	-----	-----
temperatures of	-----	9	-----	-----	-----	-----
thermal inertia of	-----	-----	xx, 57, 75	-----	-----	-----
transmissivity of the	-----	-----	6	-----	-----	-----
turbidity of	-----	-----	34-35, 88, 206, 316	83	-----	-----
vertical circulation of the	-----	171	-----	-----	-----	-----
vertical mixing of the	-----	95	-----	-----	-----	-----
vertical mixing time of the	-----	6	-----	-----	-----	-----
vertical temperature profile of the	-----	161	-----	-----	-----	-----
warming and cooling of	-----	xvii, 286	-----	-----	-----	-----
water budget of the	-----	222	-----	-----	-----	-----
water vapor mixing ratio in the	-----	198	-----	-----	-----	-----
wind fields in the	-----	8	-----	-----	-----	-----
Atmosphere-ice-ocean interactions:	-----	-----	-----	-----	-----	-----
geochemical evidence for	-----	-----	-----	-----	-----	121

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Atmosphere-ocean buffer factor	-----	169	-----	-----	-----	-----
Atmosphere-ocean feedbacks	-----	182	-----	-----	-----	-----
Atmosphere-ocean interactions	-----	v, 60, 63, 64	-----	-----	-----	-----
Atmospheric and Environmental Research, Inc.	-----	217	-----	-----	-----	-----
Atmospheric carbon dioxide (see also Carbon dioxide):						
analytical methods for determining	27-30	-----	-----	-----	-----	-----
effects of forests on	-----	-----	-----	-----	151, 154, 159	-----
effects on agricultural plants of	-----	-----	-----	-----	72, 85	-----
fluctuations of	48	-----	-----	-----	-----	-----
growth anomaly of	52	-----	-----	-----	-----	-----
growth rates of	38, 51, 52	-----	-----	-----	-----	-----
increase in	xv, xvii, 6, 18, 36	-----	-----	-----	-----	-----
indirect effects of (see also Indirect effects)	-----	-----	-----	-----	4, 20, 28, 29	-----
initial concentration of	27	-----	-----	-----	-----	-----
invasion into the surface ocean of	146, 150, 152	-----	-----	-----	-----	-----
latitudinal variations in meridional transport of	54, 57, 165	-----	-----	-----	-----	-----
monitoring of	51	-----	-----	-----	-----	-----
natural variations in preindustrial level of	132-133, 166, 169, 250, 295	-----	-----	-----	-----	-----
production of	xvi, 31, 55, 255	-----	-----	-----	11	-----
projections of	65-70	-----	-----	-----	-----	-----
	22, 78, 102-104, 217, 222, 224, 249, 267, 270-272, 278, 279, 280-281	-----	-----	-----	v, vii, 12	-----
seasonal amplitude of seasonal variations in	191	-----	-----	-----	-----	-----
	38, 42, 44, 49, 51-55, 57, 131, 132, 134, 165, 186	-----	-----	-----	-----	-----
sinks of	xv, 11, 98, 166, 198, 252, 253	-----	-----	-----	-----	-----
sources of	xv, 166, 252, 253	-----	-----	-----	-----	-----
stages of production	27	-----	-----	-----	-----	-----
steady-state values of	102	-----	-----	-----	-----	-----
uptake of excess	90	-----	-----	-----	-----	-----
vertical profiling of	28, 45	-----	-----	-----	-----	-----
Atmospheric carbon dioxide abatement policies	12	-----	-----	-----	-----	-----
Atmospheric carbon dioxide buildup:						
detection of	-----	-----	-----	-----	20, 30, 58	-----
effects on forests of	-----	-----	-----	-----	153-158	-----
effects on human health of	-----	-----	-----	-----	173-202	-----
effects on vegetation of	-----	-----	-----	-----	vii, 55, 217	-----
effects on water resources of	-----	-----	-----	-----	34-35, 54	-----
effects on weather and climate of	-----	-----	-----	-----	12-19	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Atmospheric carbon dioxide buildup (continued)					61	
methods to assess the effects of potential scope of	-----	-----	-----	-----	34, 37, 218	-----
Atmospheric carbon dioxide concentrations	77, 177, 270	-----	-----	70	20	-----
annual mean	41, 43, 48, 50, 143	-----	-----	-----	-----	-----
anthropogenic direct effects of doubling	35, 47, 152, 190 xv, xxi, 11, 145, 272, 279, 281	-----	-----	-----	3-4	-----
global average historical levels of	42-43 18, 31, 32, 34-37, 249, 250	-----	-----	-----	-----	-----
preatthropogenic	6, 32, 101, 152-153	-----	-----	-----	-----	-----
trends in tropospheric variations in	44 10, 17, 27, 32-33, 35, 37-54, 57, 97-98, 102, 145	-----	-----	-----	xix, 11, 12	-----
Atmospheric carbon dioxide distributions	145	-----	-----	-----	-----	-----
Atmospheric carbon dioxide emissions:						
average	66-70, 274	-----	-----	-----	-----	-----
global	71	-----	-----	-----	-----	-----
growth rates of	xx, xxi, xviii, 66, 72, 237	-----	-----	-----	-----	-----
projected	70-78, 260, 262	-----	-----	-----	-----	-----
Atmospheric carbon dioxide flask sampling	40-42, 132	-----	-----	-----	-----	-----
Atmospheric carbon dioxide fluxes	268	-----	-----	-----	-----	-----
Atmospheric carbon dioxide measurements	5, 38, 54, 57, 145, 201, 255, 276, 280, 295	-----	-----	-----	-----	-----
Atmospheric carbon dioxide partial pressure:						
fluctuation in surface waters of	19	-----	-----	-----	-----	-----
Atmospheric carbon dioxide projections:						
uncertainties in	276-280	-----	-----	-----	-----	-----
Atmospheric carbon dioxide zonal gradients	50-52	-----	-----	-----	-----	-----
Atmospheric circulation	-----	61, 63, 73, 157, 265, 276	-----	180	14	-----
anomalies in changes in	50, 168	-----	-----	-----	-----	39
Atmospheric energy transfer mechanisms	-----	175	-----	-----	75	137

Atmospheric forcing

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Atmospheric forcing of water motion	-----	-----	-----	-----	114	-----
Atmospheric general circulation models (see Models, general circulation)	-----	-----	-----	-----	-----	-----
Atmospheric linkages	48	-----	-----	-----	-----	-----
Atmospheric measurements	-----	224-225	-----	-----	-----	-----
Atmospheric pressure distributions	-----	-----	-----	-----	115, 125	-----
Atmospheric temperatures: distribution of	-----	-----	-----	-----	-----	48, 49, 74
Atmospheric turbidity	-----	-----	-----	-----	13	-----
Atmospheric turbulence: dispersal of biological materials by	-----	-----	-----	-----	190	-----
Atmospheric window: definition	-----	30, 263	-----	-----	-----	-----
ATP	-----	-----	-----	58	-----	-----
Australia	44	129, 132, 249	158, 160	-----	35, 42, 45, 127	-----
Avitaminosis	-----	-----	-----	-----	178	-----
Axel Heiberg Island	-----	-----	-----	-----	-----	24, 146, 148
Azore Islands	-----	204	-----	-----	-----	-----

B

Backpressure: glacial reduction of ice-stream	-----	-----	-----	-----	301	-----
Backstress (glacial)	-----	-----	-----	-----	302	-----
Backwelling	156	-----	-----	-----	53, 55, 318-324	-----
BACROS	-----	-----	45	-----	63	-----
Bacteria (see also Diseases, bacterial) dispersal of survival in the atmosphere of	-----	-----	-----	-----	190-191, 199, 201	-----
Bacterial autotrophs	97	-----	-----	-----	190	-----
Balance velocities: computed distribution of	-----	-----	-----	-----	190, 199	-----
Baltic Sea	-----	-----	121, 122	-----	173, 175, 320-321	-----
Baltic Shield	-----	-----	-----	-----	174, 175	-----
Band strength: definition	-----	30	-----	-----	86	-----
Barents Sea	-----	-----	126, 127	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Barley	-----	-----	-----	67, 71, 103, 105-109, 111, 114, 218-221	75	-----
Barnyard grass	-----	-----	-----	122	-----	-----
Baroclinic adjustment lapse rate	-----	299, 316	-----	-----	-----	-----
Baroclinic adjustment process	-----	88, 301	-----	-----	-----	-----
Baroclinic disturbances	-----	63	-----	-----	-----	-----
Baroclinic eddies:	-----	-----	-----	-----	47	-----
modeling of portrayal of	-----	77	-----	-----	-----	-----
Basal freezing	-----	-----	-----	-----	23	-----
Basal growth	-----	-----	-----	-----	172	-----
Basal mass balance	-----	-----	-----	-----	33	-----
Basal melting (see also Ice shelves, basal melting of) carbon dioxide-induced climate change and dependence of on ocean temperature	-----	-----	-----	-----	123, 187, 197, 210, 314	312
effects of on iceberg calving rates of	-----	-----	-----	-----	322	-----
variation of	-----	-----	-----	-----	5, 31, 54, 55, 120, 203, 317	23, 28, 205
Basal meltwater	-----	-----	-----	-----	118, 119	-----
Basal reflectivity	-----	-----	-----	-----	188	-----
Basal shear stress	-----	-----	-----	-----	223, 225, 226, 302	-----
Basal sliding	-----	-----	-----	-----	3, 51-53, 63, 67	-----
Baseline climate	-----	-----	4, 166, 181	-----	-----	-----
Baseline observatories	38, 249	-----	-----	-----	-----	-----
Bathymetric irregularities	-----	-----	-----	-----	112	-----
Bathymetry	-----	-----	-----	-----	126	-----
Bathythermograph data	-----	-----	97-98	-----	-----	-----
BEAM-1982	-----	-----	-----	141	-----	-----
Beam analysis	-----	-----	-----	-----	288	-----
Beardmore Glacier	-----	-----	-----	-----	188	-----
Beaufort Sea	-----	-----	-----	-----	119	-----
Beggar's lice	-----	-----	-----	121	-----	-----
Bellingshausen Sea (see also Amundsen-Bellingshausen coastline)	-----	-----	-----	-----	5, 48, 51, 314	-----
Bentley Subglacial Trench	-----	-----	-----	-----	-----	283
Bering Sea	-----	-----	-----	-----	106, 111, 114, 122, 123, 125, 139	-----
Berkner Island	-----	-----	-----	-----	-----	302, 305
Bermuda Biological Station	-----	-----	-----	-----	-----	105

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level	
Bermuda sea level	-----	-----	-----	-----	-----	16, 18, 19, 104-115	
Beta factor (Biotic growth factor)	86, 130, 158, 273, 297	-----	-----	xxiv, 42-43, 78, 174-180, 182	-----	-----	
<i>Betula nana</i>	-----	-----	-----	123,	-----	-----	
Bibliography	-----	-----	-----	8	-----	-----	
Bicarbonate concentrations	-----	-----	-----	165	-----	-----	
Bicarbonate ions	83, 85	-----	-----	-----	100	-----	
Bilello's equation	-----	-----	127	-----	-----	-----	
Biochemistry: human	-----	-----	-----	-----	173, 175, 177	-----	
Biogeochemical cycle	xvi, xxii, 21, 177-182, 282, 293	-----	-----	-----	-----	-----	
Biological events: timing of	-----	-----	-----	-----	83	-----	
Biological processes	95, 148	-----	-----	-----	-----	-----	
Biological productivity	103-104	-----	-----	-----	-----	-----	
Biological records	-----	64	-----	-----	-----	-----	
Biologically mediated fluxes	296	-----	-----	-----	-----	-----	
Biomass	119, 200, 230, 292	-----	4	-----	-----	-----	
burning of	-----	196, 197, 199	-----	-----	-----	-----	
definition	-----	60, 63	-----	-----	-----	-----	
estimates of	121, 181	-----	-----	-----	-----	-----	
partitioning of	-----	-----	-----	157, 159	-----	-----	
use as fuel of	78, 280	-----	-----	-----	-----	-----	
Biomass accumulation	-----	-----	-----	xxiii, 57, 64, 102, 103, 105-109, 111, 113, 114, 136, 158, 163, 164, 173, 182, 199, 207, 210, 216, 219, 224, 225, 232, 235, 238, 239, 243, 251, 252, 253, 261, 265, 266	-----	-----	-----
Biomass by region or ecosystem	117, 263	-----	-----	-----	-----	-----	
Biomass change of trees	-----	-----	-----	-----	158, 163	-----	
Biosphere	8-9, 55, 177, 205, 275, 298	xxi	-----	173, 176, 181	-----	-----	
carbon dioxide fluxes of	45, 47, 252, 267, 275, 277	-----	-----	-----	-----	-----	
exchange functions of	166	-----	-----	-----	-----	-----	
exchanges in	37, 45, 55, 57	-----	-----	-----	-----	-----	
releases in	36, 56, 262	-----	-----	-----	11, 150, 154	-----	
terrestrial	-----	-----	-----	-----	-----	-----	
Biosphere-induced oscillations	167	-----	-----	-----	-----	-----	
Biota	205, 291	-----	-----	-----	-----	-----	
marine	169, 188	-----	-----	-----	-----	-----	

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Biota (continued)						
terrestrial	xix, 115, 116, 121, 131, 168	-----	-----	-----	-----	-----
Biotic effects	-----	-----	-----	-----	101, 103-111, 139	-----
Biotic environments	-----	-----	-----	157	-----	-----
Biotic feedback	134	-----	-----	-----	-----	-----
Biotic flux	122, 129-133	-----	-----	-----	-----	-----
historic	133-134, 253	-----	-----	-----	-----	-----
net	115, 133	-----	-----	-----	-----	-----
Biotic growth factor	-----	-----	-----	xxiv, 42-43, 78, 174-180, 182	-----	-----
Biotic response to changes in climate	132	-----	-----	-----	-----	-----
Birth defects (human): seasonal variations in	-----	-----	-----	-----	199, 201, 212	-----
Birth rates (human): seasonal patterns in	-----	-----	-----	-----	177	-----
Birth weights (human): seasonal variation in	-----	-----	-----	-----	184	-----
Bitumen	75-76	-----	-----	-----	-----	-----
Bivalves	-----	-----	-----	-----	107, 124	-----
Black body radiation	-----	29	-----	-----	-----	-----
Black cutworm moths	-----	-----	-----	-----	84	-----
Blueberry	-----	-----	-----	123	-----	-----
Bluegrass	-----	-----	-----	-----	79	-----
Body heat loss	-----	-----	-----	-----	175	-----
Body temperature: core	-----	-----	-----	-----	175, 189	-----
surface	-----	-----	-----	-----	175	-----
Bogs	197, 198	-----	-----	138, 148, 181, 211	-----	-----
Bonin Trench	-----	-----	-----	-----	-----	78
Borates	168	-----	-----	-----	-----	-----
Boreal regions current carbon content of	125-126, 197	-----	-----	137-138, 142, 211	-----	-----
Boreal trees: extinction of	-----	-----	-----	-----	xvii, 161, 162	-----
Borneo	133	-----	-----	-----	-----	-----
Boston sea level	-----	-----	-----	-----	-----	14, 17
Bottom crevasses: roles of	-----	-----	-----	-----	-----	124
Bottom water	197	-----	-----	-----	-----	-----
Bottom-water formation rates of	-----	276	-----	-----	-----	21, 118 121, 122
Boundary conditions	-----	66-67, 158	-----	-----	-----	-----
Boundary layer processes: parameterization of	-----	69, 262, 323	-----	-----	-----	-----

Box budgets

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Box budgets	-----	-----	-----	24	-----	-----
Branching	-----	-----	-----	70, 71, 83, 86, 130, 160, 187, 198, 207	-----	-----
Breeding: plant	-----	-----	-----	xxiv, 115, 140, 198, 201	-----	-----
Breeding cycles of crops and trees	-----	-----	-----	145, 189, 201	-----	-----
BRIND	-----	-----	-----	45	-----	-----
Bristlecone pines	-----	-----	-----	180, 198	-----	-----
Britain	-----	-----	120	-----	-----	-----
British Columbia	-----	247	-----	-----	98, 111, 112	-----
Bromine	-----	210	-----	-----	-----	-----
Brooks Range	-----	-----	-----	-----	-----	141
Brunt Ice Shelf	-----	-----	-----	-----	-----	200, 202
Brunt-Vaisala buoyant frequency	-----	178	-----	-----	-----	-----
Buffer effect	86, 130, 257, 269	-----	-----	-----	-----	-----
Buffering agents in seawater	-----	-----	-----	-----	100	-----
Buffering of seawater	-----	-----	-----	181	-----	-----
Buoyancy fluxes across the sea	-----	-----	-----	-----	-----	106
Buoys: drifting	84, 92	-----	-----	-----	-----	-----
Bureau of Mines	18	-----	-----	-----	-----	-----
Burkitt's lymphoma and climatological factors	-----	-----	-----	-----	183	-----
Business as usual scenarios	217, 240, 241, 243	-----	-----	-----	-----	-----
Byrd Glacier	-----	-----	-----	-----	-----	180, 185, 190, 315

C

C-14 to C-12 ratios	-----	-----	-----	178	-----	-----
C3 pathway of photosynthesis	-----	-----	-----	xxi, 57, 182, 191	28	-----
C3 plants	190	-----	-----	18, 60, 69, 74, 75, 78, 85, 87, 90, 112, 114, 139, 157, 158, 161, 166, 176, 178, 187, 195, 199, 200, 207, 208, 209	75	-----
C4 pathway of photosynthesis	-----	-----	-----	57, 182, 191	28	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
C4 plants	190, 201	-----	-----	xxiii, 6, 18, 60, 69, 74, 75, 78, 85, 87, 90, 114, 120, 157, 158, 161, 176, 178, 187, 194, 195, 199, 200, 207, 208, 209, 212	75	-----
Cacti	-----	-----	-----	-----	75	-----
Calcite	87-88	-----	-----	-----	105	-----
Calcium carbonate precipitation	xvi, 85, 88, 105, 193	-----	-----	-----	-----	-----
Calcium carbonate: biological deposition of	-----	-----	-----	-----	97, 103	-----
Calcrete	115	-----	-----	-----	-----	-----
Calibration protocols	17	-----	-----	-----	-----	-----
Caliche	115, 117, 120, 181	-----	-----	-----	-----	-----
Calvin cycle	-----	-----	-----	73	-----	-----
Calving (see <i>Iceberg calving</i>)						
CAM metabolism	190	-----	-----	-----	-----	-----
CAM plants	-----	-----	-----	-----	75	-----
Canada	264, 294	129, 132, 247	34, 119, 130, 131, 132, 135	-----	79, 90	60, 94, 99
Canadian Arctic	-----	-----	-----	-----	-----	143
Canadian Arctic Islands	-----	-----	-----	-----	-----	145-154
Canary Islands	-----	204	-----	-----	-----	-----
Cancer	-----	-----	-----	-----	183	-----
Cancer mortality and meteorological conditions	-----	-----	-----	-----	178, 183	-----
Cannibalism: fishery	-----	-----	-----	-----	113, 120-121, 123, 128, 139	-----
Canopy (plant)	-----	-----	-----	14, 65, 201	-----	-----
Canopy carbon dioxide uptake	-----	-----	-----	60	-----	-----
Canopy depth	-----	-----	-----	65	-----	-----
Canopy photosynthesis	-----	-----	-----	60, 65, 85, 126	-----	-----
Canopy photosynthetic rate	-----	-----	-----	xviii, 56, 60, 61, 64, 65, 187	-----	-----
Canopy resistance to water vapor and carbon dioxide	-----	-----	-----	61	-----	-----
Canopy response	-----	-----	-----	19, 60	-----	-----
Cape Grim	45, 47	-----	-----	-----	-----	-----
Cape Hatteras	-----	-----	-----	-----	-----	14
Cape Horn, Oregon	37	-----	-----	-----	-----	-----
Cape Meares, Oregon	40	196	-----	-----	-----	-----
Capelin	-----	-----	-----	-----	107	-----

Carbohydrate accumulation

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Carbohydrate accumulation in plant parts	-----	-----	-----	68, 70, 127	-----	-----
Carbohydrate partitioning	-----	-----	-----	112	-----	-----
Carbohydrate storage	-----	-----	-----	68	-----	-----
Carbohydrates: translocation of	-----	-----	-----	129, 130, 141	-----	-----
Carbon:						
atmospheric excess	5, 6, 143 90	-----	-----	-----	-----	-----
net annual accumulation of	125	-----	-----	-----	-----	-----
net annual flux of (see also Carbon fluxes)	132, 133	-----	-----	-----	-----	-----
oceanic	84-85, 182, 190	-----	-----	-----	-----	-----
terrestrial	5, 128, 158-159, 181, 251, 271	-----	-----	-----	-----	-----
Carbon-13 abundance	161	-----	-----	-----	-----	-----
Carbon-13 data	170	-----	-----	-----	-----	-----
Carbon-14 bomb	156 xviii, 92-93, 95, 99, 105, 150, 153, 169, 258	----- 46	-----	-----	-----	-----
decay rate of natural	92 93, 106	-----	-----	-----	-----	-----
surface water content of vertical distribution of	92, 153 147	-----	-----	-----	-----	-----
Carbon-14 data: oceanic	153	-----	-----	-----	-----	-----
Carbon-14 dating	29, 120	-----	-----	-----	-----	94, 95, 224
Carbon-14-to-carbon-12 ratio	156	-----	-----	-----	-----	-----
Carbon allocation	-----	-----	-----	xxi, 128, 130	-----	-----
<i>Carbon and the Biosphere</i>	-----	-----	-----	3	-----	-----
Carbon assimilation	-----	-----	-----	114	-----	-----
Carbon balance: global	256, 262	-----	-----	-----	-----	-----
Carbon budgets global	21, 187 -----	-----	-----	181	-----	-----
Carbon burial	xvi, 192, 195, 196	-----	-----	-----	-----	-----
Carbon content: vegetal	116, 128, 134, 162, 185, 189, 257	-----	-----	-----	-----	-----
Carbon cycle	v, xv, xix, 3, 4-9, 17, 21, 22, 33, 36, 47, 50, 55, 74, 77, 83-85, 115, 130, 143-171, 177-206, 280	-----	-----	3, 35, 101, 173, 176, 181, 210	v, xiv, 11, 137, 150, 154, 163-164, 197, 210	-----
global uncertainties in	----- 23, 256, 272-277	v -----	vi -----	-----	-----	-----
Carbon cycling	v, 183, 195, 203	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Carbon dioxide (see also Atmospheric carbon dioxide):						
absorption bands of	-----	29, 41, 262	-----	-----	-----	-----
airborne fraction of	-----	-----	-----	-----	11	-----
annual exchange of	28	-----	-----	-----	-----	-----
annual turnover of	4	-----	-----	-----	-----	-----
anthropogenic	11, 27, 33, 47	-----	-----	-----	11	-----
commercial sources of	-----	-----	-----	25	-----	-----
cooling rates of	-----	37, 42	-----	-----	-----	-----
dark fixation of	-----	-----	-----	5	-----	-----
deep water injections of	20	-----	-----	-----	-----	-----
direct effects on	-----	-----	167-168	-----	-----	-----
radiation of	-----	-----	-----	-----	-----	-----
distribution of	85-89	-----	-----	-----	-----	-----
effects on distribution of	-----	-----	151, 158	-----	-----	-----
precipitation from	-----	-----	-----	-----	-----	-----
indirect effects of	-----	-----	-----	43, 57, 64, 72,	xiii-xvi	-----
interactions of with light	-----	-----	-----	89, 108, 115,	-----	-----
interactions of with other	-----	-----	-----	159, 178	-----	-----
variables	-----	-----	-----	42, 72, 80, 83,	-----	-----
interactions of with pollutants	-----	-----	-----	84, 89, 90, 114	-----	-----
interactions of with salinity	-----	-----	-----	xix, xxv, 14, 18,	-----	-----
interactions of with temperature	-----	-----	-----	75-76, 83, 87,	-----	-----
interactions of with water	-----	-----	-----	89, 188, 209	-----	-----
mineral nutrients and	-----	-----	-----	xxi, xxv, 21, 74,	-----	-----
monitoring systems for	-----	-----	-----	76, 83, 87, 89,	-----	-----
partial pressure of	85-87, 90, 91,	-----	-----	188, 209, 212	-----	-----
105, 106, 143,	-----	-----	-----	19, 43, 73, 89,	-----	-----
146, 168	-----	-----	-----	109, 115, 178,	-----	-----
201, 208	-----	-----	-----	106, 115	-----	-----
postglacial concentration of	27	-----	-----	74-75	-----	-----
preindustrial concentrations	-----	-----	-----	xix, 14	-----	-----
purchase costs of	-----	-----	-----	-----	-----	-----
radiative effects of trace	-----	xix	-----	-----	-----	-----
gases and	-----	-----	-----	-----	-----	-----
radiative effects of	-----	27, 41-44, 263-264	-----	-----	-----	-----
radiative properties of	-----	50, 262-264	-----	-----	-----	-----
release rates of	66-67	164	-----	-----	-----	-----
releases of	118, 119, 122,	-----	-----	-----	-----	-----
182, 273	-----	-----	-----	-----	-----	-----
single-leaf responses to	-----	-----	-----	65	-----	-----
soil flux of	-----	-----	-----	142	-----	-----
supersaturation of	53	-----	-----	-----	-----	-----
terrestrial	20	-----	-----	-----	-----	-----
Carbon dioxide and volcanic	-----	-----	64	-----	-----	-----
forcing	-----	-----	-----	-----	-----	-----
Carbon dioxide as an	-----	-----	-----	5, 35, 46	-----	-----
ecological variable	-----	-----	-----	-----	-----	-----
Carbon Dioxide Assessment	-----	-----	79	-----	-----	-----
Committee	-----	-----	-----	-----	-----	-----
Carbon dioxide assimilation	-----	-----	-----	17, 74, 122, 173	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Carbon-dioxide-climate relationships	258	-----	-----	-----	-----	-----
Carbon dioxide concentration	-----	-----	165	-----	-----	-----
cross-switching of ecotypic differences in response to	-----	-----	-----	62	-----	-----
effects of	21	-----	-----	-----	-----	-----
effects of specific leaf area on	-----	-----	-----	68	-----	-----
effects on atmospheric ozone	-----	210	-----	-----	-----	-----
effects on carbon partitioning on	-----	-----	-----	67, 86, 212	-----	-----
effects on conductance of	-----	-----	-----	208	-----	-----
effects on crops of	-----	-----	-----	35, 71, 101, 157, 160, 177, 188, 193, 194-197	-----	-----
effects on ecosystems of	-----	-----	-----	xviii, 7	-----	-----
effects on flowering	-----	-----	-----	161	-----	-----
effects on plant reproduction	-----	-----	-----	161	-----	-----
effects on water use by plants of	-----	-----	-----	43, 61, 66	-----	-----
experimental control of global	-----	-----	-----	24	-----	-----
growth scenario of	-----	164	-----	180	-----	-----
increase of	-----	261	-----	-----	-----	-----
long-term effects of nutrients and	-----	-----	-----	xxii, 120, 168-169 21, 74, 75, 83, 89, 107, 115, 158, 159, 163, 173	-----	-----
preindustrial projections of	-----	165	-----	-----	-----	-----
short-term studies of	-----	341	-----	-----	-----	-----
soil water and	-----	-----	-----	62	-----	-----
water stress and	-----	-----	-----	89	-----	-----
whole-season effects of	-----	-----	-----	19, 21	-----	-----
-----	-----	-----	-----	64	-----	-----
Carbon dioxide effects: detection strategies for (see Detection strategies)	-----	-----	-----	-----	-----	-----
Carbon dioxide emissions	65-72, 227, 229, 230, 258, 274	18, 163, 164	-----	-----	-----	-----
Carbon dioxide enrichment effects:	-----	-----	-----	27, 28, 35, 147	-----	-----
predictions of	-----	-----	-----	-----	-----	-----
Carbon dioxide enrichment methods	-----	-----	-----	25, 27, 60	-----	-----
Carbon dioxide exchange rate	-----	-----	-----	111-112	-----	-----
Carbon dioxide fertilization	21, 56, 130, 144, 147, 159, 170, 179, 263-264, 273, 279, 297	-----	-----	ix, xi, 13, 166, 167, 173-174, 176, 179, 180, 188	28, 150, 159, 161, 162, 217	-----
Carbon dioxide fixing enzymes	-----	-----	-----	76	-----	-----
Carbon dioxide fluxes	-----	-----	-----	119, 143, 144, 173	-----	-----
Carbon dioxide forcing	282	-----	-----	-----	-----	-----
Carbon dioxide fumigation	-----	-----	-----	14, 144, 147, 168	155	-----
Carbon dioxide-induced climate change (see also Climate; Climate change)	-----	-----	ix, 31, 48, 64, 184	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Carbon dioxide-induced climate change	-----	ix, xvii, 285, 339, 341, 361	-----	-----	-----	-----
basal melting and dependence of on control climate	-----	104-107	-----	-----	-----	312
detection of	-----	-----	xvii, xxi, 3, 9, 48, 153, 155, 158, 160, 166, 169, 173, 181	-----	-----	270
indirect effects of rate of	282	-----	-----	1-276	-----	-----
seasonal nonuniformity	-----	267	-----	-----	-----	-----
simulations of	-----	101	-----	-----	-----	-----
transient effects of	-----	83-144	-----	-----	-----	-----
-----	-----	262	-----	-----	-----	-----
Carbon dioxide-induced climatic perturbations: index of	-----	-----	129	-----	-----	-----
Carbon dioxide-induced signal	4, 29	14, 163	xviii, xxii, xxv, xxvii, 6, 9, 10, 11, 151 11, 156, 160, 167, 175	-----	-----	-----
detection of	-----	-----	-----	-----	-----	-----
Carbon dioxide-induced temperature change	-----	266, 268	-----	-----	-----	-----
Carbon Dioxide Information Center	17, 38, 40, 241	-----	-----	8	-----	-----
Carbon dioxide levels	-----	-----	-----	-----	11-12	-----
Carbon dioxide moisture interaction	-----	-----	-----	139, 159	-----	-----
Carbon Dioxide Research Division	-----	-----	-----	-----	v	-----
Carbon Dioxide Research Program	241	-----	-----	-----	vii, xiii, 3, 60, 61, 129, 197	-----
Carbon dioxide responses: long and short term time courses of	-----	-----	-----	xviii, 180 123	-----	-----
Carbon dioxide seasonal amplitude	-----	-----	-----	179	-----	-----
Carbon dioxide seeps	-----	-----	-----	144	-----	-----
Carbon dioxide transfer conductance	-----	-----	-----	64	-----	-----
Carbon dioxide treatment: low	-----	-----	-----	58	-----	-----
Carbon Dioxide Vegetation Response Research Program	-----	-----	-----	101	-----	-----
Carbon dioxide warming: consensus on	-----	185	-----	-----	-----	-----
Carbon disulfide: sources and sinks of	-----	199	-----	-----	-----	-----
Carbon exchange rate	-----	-----	-----	216, 222, 223, 230, 231, 235, 237, 243, 245-248, 263, 264	-----	-----

Carbon fixation

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Carbon fixation	-----	-----	-----	37, 38, 55, 67, 111, 113, 120, 128, 207, 210 66	28, 75, 147	-----
inhibition of	-----	-----	-----	-----	-----	-----
Carbon flux rates	182-190, 198, 200	-----	-----	-----	-----	-----
Carbon fluxes	xix, 4, 96, 123-124, 143-145, 170, 179, 194, 196, 200, 204	-----	-----	7, 120, 127, 128, 173 11	-----	-----
biospheric	22	-----	-----	-----	-----	-----
current estimates of	23, 126	-----	-----	-----	-----	-----
oceanic	22	-----	-----	-----	-----	-----
sedimentary	195	-----	-----	-----	-----	-----
terrestrial	18, 126, 147, 252	-----	-----	-----	-----	-----
Carbon isotope data from deep sea sediment cores	-----	240	-----	-----	-----	-----
Carbon isotopes ratios of	34, 152, 295 20	-----	-----	-----	-----	-----
Carbon monoxide sources of atmospheric	188, 198, 297	196, 223 196	-----	-----	-----	-----
Carbon releases	66-67, 121-122, 125, 128, 130, 131, 146, 163, 198	-----	-----	-----	-----	-----
Carbon reservoirs principal	xv, 4, 9, 180	-----	-----	-----	11	-----
Carbon sequestering	-----	-----	-----	xviii, xxii, xxiii, 3, 7, 35, 119, 135-136, 138, 142, 145, 148, 212 212	-----	-----
reversals of	-----	-----	-----	-----	-----	-----
Carbon sinks	8, 19, 21, 126, 143, 145, 200, 253	-----	-----	173	3, 11, 151, 154	-----
Carbon sources terrestrial	145, 162	-----	-----	173	3, 11, 151, 164	-----
Carbon stocks	116, 127, 129, 133, 143, 145, 159, 162-163	-----	-----	-----	-----	-----
estimates of	128, 134, 187	-----	-----	-----	-----	-----
Carbon storage	xx, 18, 115, 130, 131, 158-159, 162-164, 170, 190, 191, 197, 198, 199, 201, 203, 264, 266, 297	-----	-----	66, 137	163-164	-----
Carbon storage capacity	4	-----	-----	-----	-----	-----
Carbon storage pools	-----	-----	-----	6, 182	-----	-----
Carbon-to-nitrogen ratios	263	-----	-----	43, 134, 135, 139, 162, 166, 169, 199, 200, 201, 212	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Carbon-to-phosphorus ratios	192	-----	-----	188, 199, 200, 201, 212	-----	-----
Carbon-to-sulfur ratios	196, 197, 299	-----	-----	-----	-----	-----
Carbon transport pool: soluble	-----	-----	-----	122	-----	-----
Carbon uptake	131, 150, 153	-----	-----	xxiii, 22	-----	-----
Carbonate fluxes	195	-----	-----	-----	-----	-----
Carbonate ion	85, 156	-----	-----	-----	-----	-----
Carbonate minerals dissolution of	9, 106, 115, 187	-----	-----	-----	-----	-----
Carbonate sediments	97	-----	-----	-----	-----	-----
Carbonate sediments	5, 7, 31, 55	-----	-----	-----	-----	-----
Carbonic acid	-----	-----	-----	-----	100	-----
Carbonyl sulfide sources and sinks of tropospheric lifetime of	-----	193, 198	-----	-----	-----	-----
Carbonyl sulfide sources and sinks of tropospheric lifetime of	-----	199	-----	-----	-----	-----
Carbonyl sulfide sources and sinks of tropospheric lifetime of	-----	199	-----	-----	-----	-----
Carboxylation capacity	-----	-----	-----	123	-----	-----
<i>Carex bigelowii</i>	-----	-----	-----	124	-----	-----
Cascades	-----	-----	-----	-----	-----	141, 223
Case study approach	-----	-----	-----	-----	46-53	-----
Catchments	-----	-----	-----	-----	82	-----
Catfish	-----	-----	-----	-----	99	-----
Cattle	-----	-----	-----	-----	76, 79	-----
open range production of regional shifts of breeds of	-----	-----	-----	-----	79	-----
open range production of regional shifts of breeds of	-----	-----	-----	-----	76	-----
Caucasus, The	-----	-----	135	-----	-----	141
Cement production	68, 143	-----	-----	-----	-----	-----
Cenozoic Era	200	-----	-----	-----	-----	-----
Central America	131	132	-----	-----	-----	-----
Central Physical Observatory at St. Petersburg	-----	-----	38	-----	-----	-----
Cerebrovascular disease	-----	-----	-----	-----	178, 179, 181	-----
CERES	-----	-----	-----	45	-----	-----
CERL	-----	-----	-----	25	-----	-----
Challenger, H.M.S.	-----	-----	93	-----	-----	-----
Chambers:	-----	-----	-----	-----	-----	-----
branch	-----	-----	-----	13	-----	-----
closed (see also Chambers, tracking)	-----	-----	-----	19, 111	-----	-----
controlled environment	-----	-----	-----	19, 26, 28, 82, 83, 89, 158, 213	-----	-----
advantages and disadvantages of soil studies in	-----	-----	-----	18, 26-27	-----	-----
growth	-----	-----	-----	60 xix, xxi, 13, 18, 26-27, 28, 84, 115, 145 xviii, xix, xx, 13, 14, 18, 27, 55, 82, 83, 188	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Chambers (continued)						
leaf	-----	-----	-----	xviii, 13, 17, 26, 28, 169	-----	-----
open-top	-----	-----	-----	xix, 14, 15, 22, 26, 27, 62, 111, 147, 157, 165, 213	-----	-----
SPAR tracking (see also Chambers, closed)	-----	-----	-----	19 21-22, 26, 28, 213	-----	-----
Chandler wobble	-----	-----	-----	-----	-----	97
<i>Changing Climate</i>	240	-----	-----	-----	-----	10
Channel depth reductions	-----	-----	-----	-----	44	-----
Channel storage of water	-----	-----	-----	-----	27	-----
Chapman Symposium	192	-----	-----	-----	-----	-----
Chappuis bands of ozone	-----	29, 208	-----	-----	-----	-----
Charcoal	126, 161, 164, 257	-----	-----	-----	-----	-----
Charcoal rot	-----	-----	-----	-----	84	-----
Charge-balance equation	85	-----	-----	-----	-----	-----
Charleston sea level	-----	-----	-----	-----	-----	18, 110, 112, 114
Charts:	-----	-----	-----	-----	-----	-----
Antarctic-ice	-----	-----	-----	-----	-----	121
Chemical composition of the atmosphere and ocean	-----	64	-----	-----	-----	-----
Chemical rates of reaction	-----	262, 269	-----	-----	-----	-----
Chemical records	-----	64	-----	-----	-----	-----
Chenopodium album	-----	-----	-----	131, 158	-----	-----
Chernozem soils	-----	-----	-----	-----	80	-----
Chile	-----	129, 247	-----	-----	127	-----
China	71	-----	38, 45, 64, 131, 132, 159, 160	-----	90, 97	-----
Chlorella	-----	-----	-----	165, 162	-----	-----
Chlorofluorocarbons	xviii, 90, 92, 94, 105, 146, 156, 165, 242, 258, 282, 293	5, 195-196, 206, 223, 264, 268-269	18, 23, 24, 26, 167, 183	-----	-----	121
effects on ozone of future emissions of	-----	209, 218, 219 218, 219	-----	-----	-----	-----
Chlorophyll	-----	-----	-----	158	-----	-----
Chloroplasts	-----	-----	-----	58, 69, 120	-----	-----
Cholera	-----	-----	-----	-----	193	-----
Christchurch	40	-----	-----	-----	-----	-----
Chronic disease aggravation	-----	-----	-----	-----	175	-----
Chrysanthemum	-----	-----	-----	67	-----	-----
Chukchi Sea	-----	-----	-----	-----	119	-----
Cimarron River Channel	-----	-----	-----	-----	44	-----
Cincinnati	-----	203	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Circulation:						
atmospheric	48, 165-168	-----	-----	-----	-----	-----
continental shelf	-----	-----	-----	-----	-----	50, 121, 124
deep ocean	93	-----	-----	-----	-----	-----
upper ocean	93	-----	-----	-----	-----	-----
Circumpolar deep water (see also Deep water)	-----	-----	-----	-----	-----	4, 21, 50, 116, 119, 310, 313
Circumpolar deep water:						
flux of temperature projections for	-----	-----	-----	-----	-----	326
-----	-----	-----	-----	-----	-----	62, 120
Cirrus clouds	-----	310	-----	-----	-----	-----
City planning	-----	-----	-----	-----	196	-----
Clausius-Clapeyron equation	-----	88, 316	-----	-----	-----	-----
Clay-humus complex	-----	-----	-----	-----	28	-----
Clear sky radiation	-----	38	-----	-----	-----	-----
Clemson University	-----	-----	-----	13	-----	-----
CLIMAP reconstruction	-----	-----	-----	-----	-----	281
Climate	-----	-----	-----	-----	25-31, 197	-----
animal breeds and definition	-----	-----	-----	-----	77-78	-----
effects on airborne pathogens and allergens of extreme:	-----	xviii, 4	3	-----	12	-----
no production of genetic changes by	-----	-----	-----	-----	190-192, 213, 214	-----
fluctuations of forcing of the future	34, 190, 198	-----	-----	-----	-----	-----
-----	-----	xviii, 184	-----	-----	-----	-----
-----	102	ix, xviii, xxiv, 12-19, 83-144, 275, 279, 340	-----	-----	-----	-----
information on linkages with vegetation and the hydrologic system of natural (see Natural climate)	-----	-----	-----	76	-----	-----
-----	-----	-----	-----	-----	27-29	-----
physical processes of records of	-----	63-64, 205-216	-----	-----	-----	-----
-----	-----	9-12, 17, 59, 64, 183, 222, 267, 270, 278, 325	-----	-----	-----	-----
-----	-----	xxiv, 4, 279	-----	-----	-----	-----
-----	-----	59, 60, 73, 96, 262, 278, 279	-----	-----	-----	-----
-----	-----	xx, 263, 323	-----	-----	-----	-----
regional and seasonal features of seasonal variation of	-----	277	-----	-----	-----	-----
-----	-----	151	-----	-----	-----	-----
Climate change (see also Carbon dioxide-induced climate change)	95, 188, 195, 200, 264, 266, 280, 282	-----	-----	-----	v, xiii, xiv-xvi, 4, 12	-----
agriculture and anthropogenic	-----	3, 62, 134, 141	-----	-----	74, 75-91, 195	-----
carbon dioxide and trace gas induced	3, 104	-----	23, 179, 184	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Climate change (continued)						
carbon dioxide-induced (see also Carbon dioxide-induced climate change; Climate)	3, 34, 55, 130, 145, 263, 266, 282	-----	-----	6, 66, 137, 145, 181, 192, 194-197	xv, xvi, 3, 4, 13, 53-55, 163	ix, 10, 40-41, 62, 98, 241
detection of catalog of expected causes of past	-----	-----	10	-----	-----	270
characteristics of decadal and longer definition	-----	xxiii, 17-19, 64, 239-241, 246-249, 253, 265, 269-270, 279	-----	-----	-----	-----
definition	64-65, 160	-----	-----	-----	-----	-----
detection of driving factors of dynamic response to effects of on glacial accumulation and ablation	-----	182	-----	-----	-----	-----
effects of on ice sheet grounding lines	5	3	-----	74	-----	-----
extent of fishery response to	-----	xvii, 166 163-169	-----	-----	-----	255-257, 264-265 207
forest response to geography of indirect effects on human health of	-----	-----	-----	-----	xv, xix 6, 37, 97-140, 212-218, 220	-----
interaction with vegetation changes of	-----	-----	-----	147-164	154	-----
-----	-----	-----	-----	174	174	-----
natural causes of parameters of past	239, 278	-----	-----	-----	-----	-----
persistent	-----	-----	-----	29	13, 131	-----
polar amplification of (see also Temperature changes, poleward amplification of; Precipitation, poleward amplification of)	92, 267	-----	-----	174	-----	-----
potential effects of precipitation and predictions of projected rate of	-----	-----	-----	5, 18, 37	-----	-----
adaptation to by society	9, 11, 12	-----	-----	196	-----	-----
projections of	55, 272	-----	-----	196	17, 50, 128, 185	-----
record of	-----	-----	165	-----	62	-----
regional	-----	267-268	-----	-----	xv, 31, 163, 175, 216	-----
scenarios of	-----	9, 11, 12	-----	30	30	-----
scenarios of	-----	7, 166, 170, 180	-----	209	-----	-----
scenarios of	-----	241-246	-----	76, 196	vii, viii, xiv, xv, xix, 5, 35, 71, 74, 75, 77-79, 81, 85, 105, 174, 209, 212, 213, 214, 215	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Climate change (continued)						
seasonal					vii, viii, xiv, xv, xix, 71, 74, 75, 81, 101, 105, 154, 209, 213, 214, 215, 216	
sensitivity to					32	
static response to						261-264
statistical tools for						
documenting						
temperature and						
timing of expected						
transient			10			
variability of future		154-174				
Climate-chemistry			64			
interactions		xxiii, 193, 205, 207-210, 213, 219, 222, 268-269				
Climate data			xx, 9, 31			
anomaly patterns in			31			
carbon-dioxide-induced			160, 180			
warming and						
forcing factors and			31			
improvement, assembly, and			xxii, 47, 182			
integration of						
spatially averaged time			31			
series of						
Climate events and processes:						
time scales of		62				
Climate factors in fish					124-125	
abundance						
Climate forcing						252
Climate forcing factors			xvii, xxii, 3, 31, 64, 71, 83, 84			
Climate-induced shelter change					196	
Climate limitations on crops					77	
Climate: Long-Range		240				
Investigation, Mapping, and						
Prediction						
Climate modeling			179, 185		14-19, 158-168	
Climate models (see Models,						
climate)						
Climate modification:						
intentional		169				
Climate monitoring			183			
Climate projections			64, 165, 180			
Climate records			166, 180			
homogeneity of			35			
Climate response:						
determining the		xx-xxii, 6, 153-156, 265-266, 331				
latitudinal variation of		268				
linear vs nonlinear		328-331				
patterns of		243, 253				

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Climate response (continued)						
regional differences in	-----	ix, 175	-----	-----	-----	-----
Climate response curves	-----	328, 331-333	-----	-----	-----	-----
Climate response function: definition	-----	-----	-----	-----	-----	267
Climate scenarios	-----	241-245	-----	79, 193	-----	-----
summer	-----	246	-----	-----	-----	-----
winter	-----	245	-----	-----	-----	-----
Climate sensitivity	-----	xxii, 59, 154, 171, 174, 263, 266-267, 326, 328, 331	-----	-----	-----	-----
Climate shifts	-----	-----	-----	-----	xvii, xviii, 35	-----
Climate signal	-----	-----	-----	-----	-----	19
definition (see also Carbon dioxide-induced signal)	-----	14	-----	-----	-----	-----
Climate stabilization	-----	-----	-----	-----	164	-----
Climate statistics	-----	14	-----	-----	-----	-----
Climate system	-----	5, 261, 265, 325	-----	-----	-----	-----
components of the	-----	5-8, 60-62, 261-263, 276	-----	-----	-----	-----
energy transfer processes	-----	8-9, 27	-----	-----	-----	-----
external driving force of the	-----	193	-----	-----	-----	-----
external influences on	-----	64	-----	-----	-----	-----
interactions among the components of	-----	60, 324	-----	-----	-----	-----
internal driving mechanisms of	-----	65	-----	-----	-----	-----
perturbations to	-----	193, 261, 277	-----	-----	-----	-----
physical laws governing the	-----	265	-----	-----	-----	-----
Climate trends	-----	-----	-----	-----	-----	207
Climate variability	-----	xxv, 16, 59, 253, 279, 324	xvii, 5	-----	xiv, xv, 29-30, 74-75, 85, 86, 88, 175, 184, 209, 216	-----
definition	-----	5	-----	-----	-----	-----
estimates of	-----	-----	-----	-----	41, 210	-----
natural	-----	253, 261	-----	-----	-----	-----
definition	-----	14	-----	-----	-----	-----
Climate variables	-----	-----	-----	-----	14, 175, 198-200	-----
effects on trees of	-----	-----	-----	-----	150, 153	-----
maps of	-----	-----	-----	-----	160	-----
projections of	-----	-----	-----	-----	209	-----
regional:	-----	-----	-----	-----	162	-----
estimates of	-----	-----	-----	-----	-----	-----
Climate variance:	-----	-----	-----	-----	35, 154, 162	-----
projections of	-----	-----	-----	-----	-----	-----
Climate warming	103, 104, 278	-----	-----	-----	-----	-----
consensus on	-----	185	-----	-----	-----	-----
ice melting associated with	-----	-----	-----	-----	303, 309-313	-----
iceberg calving associated with	-----	-----	-----	-----	302-303, 309-313	-----
societal impacts of	-----	xxiv, 9, 11, 12	-----	-----	30	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Climate warming and pest survival	-----	-----	-----	-----	85	-----
Climate zones	-----	4	-----	-----	-----	-----
Climatic analogs: definition	-----	12	-----	-----	-----	-----
Climatic anomaly: definition	-----	4	-----	-----	-----	-----
Climatic noise (see Noise, climatic)	-----	-----	-----	-----	-----	-----
Climatic optimum: definition postglacial	-----	18 250	-----	-----	-----	-----
Climatic variation: definition	-----	4	-----	-----	-----	-----
Closed loop environmental controls	-----	-----	-----	13	-----	-----
Clothing	-----	-----	-----	-----	xviii, 175	-----
Cloud-cover feedback	-----	88, 89, 138, 304-311, 317	114	-----	-----	-----
Cloud feedbacks	-----	ix, xxv, 16, 50, 88, 89, 137, 141, 143, 155, 215, 222, 276, 302, 316, 350, 359	-----	-----	-----	-----
Cloud ice water path	-----	306, 307	-----	-----	-----	-----
Cloud liquid water path	-----	306, 307, 311, 313	-----	-----	-----	-----
Cloud optical depth feedback	-----	310-313, 315, 316, 317	-----	-----	-----	-----
Cloud seeding	-----	-----	-----	-----	81	-----
Cloud sensitivity parameter	-----	49	-----	-----	-----	-----
Cloudiness	-----	5, 49, 51, 87, 113, 134, 135, 137, 153, 216, 271, 296, 312	4, 112, 118, 167, 66, 76, 77 182, 183	113	-----	-----
changes in	-----	94-95, 134-137, 138, 141, 315	-----	-----	-----	-----
effect on glaciers of	-----	-----	-----	-----	248	-----
Clouds	-----	xxi, 262, 291	-----	-----	-----	-----
advection of	-----	77	-----	-----	-----	-----
albedo of	-----	48, 49, 138, 307	-----	-----	-----	-----
altitude change of	-----	87, 137, 296, 315	-----	-----	-----	-----
altitude feedback of	-----	88, 89, 138, 302-305, 316, 317	-----	-----	-----	-----
altitude of	-----	306, 307	-----	-----	-----	-----
carbon-dioxide-induced climate change and	-----	124, 271, 307, 309	-----	-----	-----	-----
changes in	-----	-----	-----	-----	41, 43	-----
characteristics of	-----	306	-----	-----	-----	-----
effects of	-----	68	-----	-----	-----	-----
effects of optical-depth variations of	-----	143, 302	-----	-----	-----	-----
effects on surface temperature	-----	49, 136, 271	-----	-----	-----	-----

Clouds

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Clouds (continued)						
formation of ice	-----	44, 68, 113 144	-----	-----	-----	-----
liquid water content of longwave and solar properties of microphysics of optical depth of	-----	144, 311 48, 49	-----	-----	-----	-----
parameterizations of parameters of radiative effects of uncertainties in radiation calculations on	-----	77 87, 88, 89, 271, 296, 307, 311, 315	-----	-----	-----	-----
Clover	-----	77, 143, 194, 263 49	-----	-----	71, 134, 135, 157, 165	77
<i>Clupea harengus harengus</i>	-----	-----	-----	-----	108	-----
Clupeid family	-----	-----	-----	-----	113, 125	-----
Coal	xx, 258, 259	-----	-----	191	-----	-----
Coal classification	72-73	-----	-----	-----	-----	-----
Coal combustion emissions from	-----	199 66-67	-----	-----	-----	-----
Coal deposits	76	-----	-----	-----	-----	-----
Coal extraction	72	-----	-----	-----	-----	-----
Coal gasification and liquefaction	76	-----	-----	-----	-----	-----
Coastal deltas	xix, 198, 297	-----	-----	-----	-----	-----
Coastal environments	104	-----	-----	-----	-----	-----
Coastal marshes	97	-----	-----	-----	-----	-----
Coastal sediments	97, 198, 253, 296	-----	-----	-----	-----	-----
Coastal waters	97	-----	-----	-----	111, 115, 139	-----
Coastal wetlands	9, 97	-----	-----	-----	-----	-----
Coccidioides immitis	-----	-----	-----	-----	192	-----
Cod	-----	-----	-----	-----	107, 108, 113, 125	-----
Cohort abundance	-----	-----	-----	-----	123	-----
Colorado River	-----	-----	-----	-----	38, 82	-----
Columbia Glacier	-----	-----	-----	-----	-----	52, 315
Columbia River	-----	-----	-----	-----	106	-----
Combustion efficiency	65	-----	-----	-----	-----	-----
Comité Special de l'Année Géophysique Internationale	-----	-----	-----	-----	-----	216
Commission of the European Communities	17	-----	-----	-----	-----	-----
Committee on Glaciology	-----	-----	127	-----	-----	46
Commodities: alterations in production of caused by climate change	-----	-----	-----	-----	77-78	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Commodities (continued)						
marketing constraints on new migration of production of prices of	-----	-----	-----	-----	78	-----
Commonwealth Scientific and Industrial Research Organization	37, 43, 45	-----	-----	-----	78-79	-----
Community Climate Model	-----	-----	114	-----	-----	-----
Competition among plants	-----	-----	-----	xviii, 119, 140, 160, 212	-----	-----
above-ground	-----	-----	-----	24, 129	-----	-----
Competition between C3 and C4 species	-----	-----	-----	161	-----	-----
Competition experiments plants multispecies	-----	-----	-----	13, 182 163, 167	-----	-----
Competitive potentials: differential	-----	-----	-----	129	-----	-----
Competitive relationships	-----	-----	-----	134, 160, 209	-----	-----
Complex Atmospheric Energetics Experiment	-----	38	-----	-----	-----	-----
Computer costs	-----	78, 265, 266, 348, 356	-----	-----	-----	-----
Computer model: definition	-----	14	-----	-----	-----	-----
Computers: use of	-----	xvii, 14, 15, 33, 78, 262, 341-344, 359	-----	-----	-----	-----
Conception rates: animal	-----	-----	-----	-----	86	-----
human	-----	-----	-----	-----	176, 177	-----
Conceptions: seasonal variations in human	-----	-----	-----	-----	176, 199, 212	-----
Condensation	-----	61, 261	-----	-----	-----	-----
Conductance: leaf	-----	-----	-----	xvii, xxv, 43, 59, 102, 105-109, 112, 115, 122, 157, 211, 220, 227, 233, 236, 240, 244, 256, 269	-----	-----
Conductive heat flux: parameterization of	-----	69	-----	-----	-----	-----
CONIFER	-----	-----	-----	42	-----	-----
Conifers	-----	-----	-----	124, 180	-----	-----
Conservation of energy	-----	265, 323	-----	-----	-----	-----
Conservation of mass	-----	265, 340, 341	-----	-----	-----	-----
Conservation of moisture	-----	265	-----	-----	-----	-----
Conservation of momentum	-----	265, 340, 341	-----	-----	-----	-----

Conservation tillage

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Conservation tillage	-----	-----	-----	193, 200	80, 84	-----
Constant density surfaces (see Isopycnal surfaces)						
Consumers of vegetation	201	-----	-----	-----	-----	-----
Contaminated water	-----	-----	-----	-----	194, 196	-----
Continental drift models of	-----	-----	-----	-----	-----	73
Continental margins	-----	-----	-----	-----	-----	94
Continental plates	xvi, 194, 205	-----	-----	-----	-----	-----
Continental shelf waters	-----	-----	-----	-----	111	-----
Continental shelf: salinity changes on the	-----	-----	-----	-----	-----	117
Continental shelves	9, 97, 106	-----	-----	-----	-----	-----
Continental slopes	-----	-----	-----	-----	112	-----
Continuous Forest Inventory	125	-----	-----	-----	-----	-----
Contour plantings	-----	-----	-----	-----	80	-----
Contouring	-----	-----	-----	-----	87	-----
Control climate used: effects on simulated results	-----	104, 108	-----	-----	-----	-----
Control simulations: definition	-----	14	-----	-----	-----	-----
Convection	-----	6, 86, 261, 291, 323	-----	-----	-----	-----
definition	-----	63	-----	-----	-----	-----
parameterization of surface sensible heat	-----	77	-----	-----	-----	-----
262	-----	-----	-----	-----	-----	-----
Convective overturning	-----	-----	-----	-----	-----	116
Conventional International Origin	-----	-----	-----	-----	-----	97, 98
Cooling episode: post-1940	-----	-----	79	-----	-----	-----
Cooling of Earth's surface (see also Temperature change; Volcanic aerosols)	-----	268	-----	-----	-----	-----
Cooling of Earth's surface: regional	-----	271	-----	-----	-----	-----
Cooling trends	-----	-----	xxi, 57, 60, 68	-----	-----	-----
Cooperative Extension Service	-----	-----	-----	-----	91	-----
Cooperative State Research Service	-----	-----	-----	-----	91	-----
Coral reef studies	-----	-----	-----	-----	137	-----
Corals	28	-----	-----	-----	-----	-----
growth rings of	49, 57, 92, 93, 95, 150, 169	-----	-----	-----	-----	-----
Cordillera Blanca	-----	-----	-----	-----	-----	219
Coriolis Effect	-----	-----	-----	-----	103	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Coriolis forces	-----	178	-----	-----	-----	-----
Coriolis parameter	-----	178	-----	-----	-----	-----
Corn	-----	-----	-----	xxi, 6, 23, 25, 57, 59, 61, 63, 68, 70, 71, 75, 77, 78, 103, 105-109, 111, 112, 114, 123, 126, 157, 158, 159, 179, 189, 192, 200, 222-229	75, 76, 77	-----
hybrid	-----	-----	-----	-----	72	-----
Corn belt shift of	-----	-----	-----	-----	72, 80, 83	-----
-----	-----	-----	-----	-----	78	-----
Corn borer	-----	-----	-----	-----	84	-----
Coronary heart disease	-----	-----	-----	-----	179-180	-----
Corrective actions	11	-----	-----	-----	-----	-----
Cosmic ray bombardment	91, 105	-----	-----	-----	-----	-----
Costa Rica	-----	-----	-----	24	-----	-----
Cotton	-----	-----	-----	xxi, 59, 61, 70, 71, 75, 90, 103, 105-109, 111, 113, 122, 176, 178, 192, 194, 230-234	72	-----
Cotton grass	-----	-----	-----	121, 123, 126, 134	-----	-----
Cottonwood	-----	-----	-----	175	-----	-----
Cotyledons: photosynthesis of	-----	-----	-----	129	-----	-----
Council for Agricultural Science and Technology	-----	-----	-----	-----	81	-----
Coupled atmosphere-ocean general circulation models (see also Models): development of	-----	144, 267	-----	-----	-----	-----
Coupled atmosphere-ocean system	-----	72, 277	-----	-----	-----	-----
Coupling of hydrologic processes and climate models	-----	-----	-----	-----	60	-----
Coupling processes	-----	xviii-xix, 63, 264	-----	-----	-----	-----
<i>Coxiella burnetii</i>	-----	-----	-----	-----	191	-----
Crack propagation (in ice)	-----	-----	-----	-----	-----	290-292
Crary Ice Rise	-----	-----	-----	-----	-----	178, 180, 190, 193, 302, 305, 306, 310, 312, 315
Creep	-----	-----	-----	-----	-----	303, 308
Creep thinning rate	-----	-----	-----	-----	-----	281
Cretaceous Period	195, 204, 205, 300	168, 240	-----	-----	-----	-----
Crevasses formation of	-----	-----	-----	-----	-----	178, 289 285-292

Critical regions

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Critical regions:						
identification of water availability in	-----	-----	-----	-----	60 60-61	-----
Crop Carbon Dioxide Doubling Response Survey	-----	-----	-----	101, 103, 105, 215-272	-----	-----
Crop photosynthetic rate	-----	-----	-----	xviii, 56, 60, 61, 64, 65, 187	-----	-----
Crop research priorities	-----	-----	-----	90	-----	-----
Crop retardation	-----	-----	-----	-----	45	-----
Crop rotation	-----	-----	-----	-----	72, 80	-----
Crop species	-----	-----	-----	-----	72, 75, 76, 77, 79, 85	-----
physiology of	-----	-----	-----	-----	86	-----
Cropping patterns	-----	-----	-----	-----	77, 85	-----
Cropping zones: shifts in	-----	-----	-----	-----	xvii, xviii, 77, 78, 79, 80, 89	-----
Crops:						
climate limitations on growth of	-----	-----	-----	-----	77, 212	-----
heat stresses on horticultural	-----	-----	-----	101, 157	-----	-----
introduction of new monoculture of	-----	-----	-----	-----	77	-----
nonforage	-----	-----	-----	55	-----	-----
planting times of responses of	-----	-----	-----	-----	77, 89	-----
rotation of winter cover	-----	-----	-----	101	-----	-----
yields of	-----	-----	-----	103	-----	-----
	-----	-----	-----	-----	79, 86	-----
	-----	-----	-----	13, 26, 56, 60, 64, 85-88, 89	-----	-----
	-----	-----	-----	191	-----	-----
	-----	-----	-----	-----	80	-----
	-----	-----	-----	ix, xx, 14, 83, 87, 101, 103-109, 112, 113, 190, 197, 221, 229, 234, 236, 242, 258, 259, 260, 262, 270, 271, 272	-----	-----
Cross breeding of animals	-----	-----	-----	-----	76, 216	-----
Crowding:						
tree	-----	-----	-----	-----	158	-----
Crude oil:						
price of (see also Oil)	67	-----	-----	-----	-----	-----
Crust of the Earth:						
cooling of	-----	-----	-----	-----	73	-----
Crustaceans	-----	-----	-----	-----	107	-----
Crustal motion	-----	-----	96, 134, 171, 172	-----	-----	-----
Cryosphere	-----	61, 72	xxviii, 111-140, 183	-----	-----	-----
data requirements for definition	-----	-----	138, 169	-----	-----	-----
records of	-----	60, 63	111	-----	-----	-----
role in climate of	-----	-----	139, 172-173, 181	-----	-----	-----
structure of the	-----	-----	111-113, 139	-----	-----	221

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Cryosphere-climate interactions	163	112				
Cryosphere response	162					
CTG signal		23, 184				
Cucumbers				58, 71		
Cultivars: development of new					76	
Cumulus convection	88, 91, 137, 141, 143, 301					
Current meters	84					
Currents (see Ocean currents)						
Cycles (see Carbon cycle; Nitrogen cycle; Phosphorus cycle; Sulfur cycle; Silicon cycle)						
Cyclogenesis		120				
Cyclone tracks and snow margin		120				
Cyclonic activity						246
Cyclonic flow of ocean currents					116	

D

Dams					39	
Dark Ages	198					
Dark respiration of plants					150	
Data: inadequacies of incompleteness of needed		221, 223, 261, 278, 344				60, 246
reference					vii, xix, 58, 59, 60, 61, 129, 134-136, 161, 162, 165, 197-202, 209, 210, 212-218 20	
Data analysis: fishery techniques needed for			26			133, 137-139
Data bases	239-240, 292		xxvii, 31, 48, 180, 183			
adequacy of			ix, 165, 170, 171, 179	48, 141, 143, 145, 210		
assembling and integrating biases in climatologic			181			
development of model validation oceanic	23, 104 91		181, 182 xviii, xix, 74, 76, 168			
				82-83		

Data bases

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Data bases (continued)						
precipitation	-----	-----	40	-----	-----	-----
snow and ice	-----	-----	111, 137	-----	-----	-----
soil	18	-----	-----	-----	-----	-----
temperature	-----	-----	76, 85, 168, 181	-----	-----	-----
terrestrial ecosystem	18	-----	-----	-----	-----	-----
Data inhomogeneities	-----	-----	32, 47, 63	-----	-----	-----
Data sets (see Data bases)						
Date of emergence	-----	-----	-----	82	-----	-----
Davidson Glacier	-----	-----	-----	-----	-----	191, 192
Davis Strait	-----	-----	126	-----	-----	-----
Day: length of	-----	-----	-----	-----	-----	34, 93
Death (see also Mortality): causes of (see names of individual causes)	-----	-----	-----	-----	174	-----
relationship to environmental conditions of	-----	-----	-----	-----	-----	-----
Decadal fluctuations	-----	-----	xxii, xxvii, 82, 85, 155, 170, 182, 184	-----	-----	-----
Deciduous species	-----	-----	-----	124, 165	-----	-----
Decomposers	xx, 159-161, 201	-----	-----	xxv, 190, 199, 201	151	-----
Decomposition	119, 122, 143, 146, 199, 263, 268	-----	-----	38, 135, 137, 139, 142, 148, 199, 208	-----	-----
Decomposition of organic soil matter	-----	-----	-----	135-136, 137, 190	-----	-----
Deep ice shelf water	-----	-----	-----	-----	-----	20
Deep ocean: heat transport to properties of salinity changes of ventilation of	-----	-----	-----	-----	-----	271 115, 129 116 19, 66, 121, 124, 131
Deep water (see also Circumpolar deep water): cooling of formation rate of freshening of salinity of temperature-salinity shift in thermal expansion of vertical mixing processes in	-----	-----	-----	-----	-----	19 18, 129, 131 19-20, 129 129, 131 134
Defense Meteorological Satellite Program	-----	-----	124	-----	-----	-----
Deforestation (see also Forests, clearing of)	xv, xix, 8, 20, 65, 96, 123-125, 268	163, 164, 196, 204, 216, 261	34	137, 180, 181, 182	11, 43, 44, 163	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Deforestation (continued)						
tropical	52, 115, 121, 124, 126, 134, 168, 297	-----	-----	-----	-----	-----
Deglaciation	34, 197	-----	-----	-----	-----	74, 99
Deglaciation events	-----	-----	-----	-----	-----	15
Delay pools	162	-----	-----	-----	-----	-----
Demand processes	-----	-----	-----	75	-----	-----
Denmark Strait	-----	-----	-----	-----	-----	129
Denmark Strait overflow	-----	-----	-----	-----	-----	131
Density:						
measurement methods for oceanic (see also Oceans, density of)	-----	-----	103	-----	-----	-----
-----	-----	-----	-----	-----	-----	2
Density gradient of oceans	-----	-----	-----	-----	102	-----
Density structure of the upper ocean (see also Oceans, density of)	-----	-----	103	-----	-----	-----
Department of Energy (see also DOE)	220, 239, 241, 242	-----	-----	-----	-----	-----
Department of Energy, Mines, and Resources (Canada)	-----	-----	132	-----	-----	-----
Department of Energy temperature and precipitation data bank	-----	-----	37	-----	-----	-----
Desalination	-----	-----	-----	-----	82	-----
Desert	180, 200	200-201, 270	-----	120, 138, 177, 200	-----	-----
Desert lowlands	-----	-----	-----	-----	37, 46	-----
Desertification	180	204	-----	-----	41, 214	-----
Dessication	-----	-----	-----	23	-----	-----
Desynchronization of spawning times and prey availability	-----	-----	-----	-----	119	-----
Detection problem	-----	-----	6	-----	-----	-----
Detection strategies	-----	-----	xxvi, 80, 165-167, 179, 181	-----	-----	-----
Detrital carbon flux	103, 105	-----	-----	-----	-----	-----
Detritus	8, 88, 96, 115, 159-161, 291	-----	-----	-----	-----	-----
Deutscher Wetterdienst	-----	-----	41	-----	-----	-----
Developing countries	xx, 57, 71, 230, 292	-----	-----	-----	34, 98, 137, 178, 184, 196	-----
Devon Ice Cap	-----	-----	-----	-----	-----	23, 24, 147, 148, 150, 151
Devonian Period	200	-----	-----	-----	-----	-----
Dew point analyzers	-----	-----	-----	60	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Diatoms	-----	-----	-----	-----	109, 116	-----
<i>Die Grosswetterlagen Europas</i>	-----	-----	38	-----	-----	-----
Diebacks of trees	-----	-----	-----	-----	151, 152, 157, 161, 162	-----
Diffusion:	-----	-----	-----	-----	-----	-----
definition	-----	63	-----	-----	-----	-----
Diffusivity	93, 100, 154, 155, 165, 168	-----	-----	-----	-----	-----
Diode laser spectroscopy	58	-----	-----	-----	-----	-----
Direct effects:	-----	-----	-----	187, 197	-----	-----
definition	-----	-----	-----	8	-----	-----
<i>Direct Effects ... : A Bibliography ...</i>	-----	-----	-----	-----	-----	-----
Direct effects of carbon dioxide on radiation	-----	-----	167-168	-----	-----	-----
Direct radiative effect	-----	205-207, 211	-----	-----	-----	-----
Direct radiative forcing	-----	xxii, 87, 155, 291, 294, 315	-----	-----	-----	-----
Disease prevalence:	-----	-----	-----	-----	173	-----
factors in	-----	-----	-----	-----	173	-----
Disease propagation	-----	-----	-----	-----	175	-----
Disease resistance of plants	-----	-----	-----	192	-----	-----
Disease-suppressive bacteria	-----	-----	-----	192	-----	-----
Disease vectors	294	-----	-----	-----	-----	-----
Diseases:	-----	-----	-----	-----	190-191, 193, 199, 201	-----
bacterial	-----	-----	-----	-----	178, 184	-----
communicable	-----	-----	-----	-----	105, 131, 132, 134, 140	-----
fish	-----	-----	-----	-----	191, 192	-----
fungal	-----	-----	-----	-----	xv, xviii, 175, 177, 178-181, 183, 189, 190,	-----
human	-----	-----	-----	-----	191, 192, 193, 194, 198, 199, 201, 212, 215	-----
aged	-----	-----	-----	-----	178	-----
cerebrovascular	-----	-----	-----	-----	178, 179, 181	-----
coronary heart	-----	-----	-----	-----	179-180	-----
heart	-----	-----	-----	-----	179-180	-----
mapping of	-----	-----	-----	-----	201	-----
organic	-----	-----	-----	-----	198, 201, 212, 213, 214, 215	-----
parasitic	-----	-----	-----	-----	194, 199, 200, 212, 213, 214, 216	-----
pathogens of	-----	-----	-----	-----	xvi, 190-192, 199, 213, 214	-----
prevalence of	-----	-----	-----	-----	173, 193	-----
rickettsial	-----	-----	-----	-----	191, 199	-----
vectors of	-----	-----	-----	-----	40, 175, 193	-----
outbreaks of animal	-----	-----	-----	-----	86	-----
outbreaks of human	-----	-----	-----	-----	42	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Diseases (continued)						
plant	-----	-----	-----	-----	71, 80, 84	-----
plant vulnerability to resistance of animals to	-----	-----	-----	-----	76	-----
tree	-----	-----	-----	-----	76	-----
viral	-----	-----	-----	-----	213	-----
181, 193						
Disko Bugt	-----	-----	-----	-----	-----	166
Dissipative processes: parameterization of	-----	77	-----	-----	-----	-----
Dissolution of calcium carbonate	102	-----	-----	-----	-----	-----
Dissolved oxygen	89	-----	-----	-----	-----	-----
Diurnal changes	-----	-----	-----	15	-----	-----
DOE Carbon Dioxide Research Program	-----	-----	-----	-----	v, vii, xii, 3, 60, 61, 129, 197	-----
DOE Climate Effects Program	-----	-----	-----	-----	v, 58	-----
DOE Vegetation Effects Program	-----	-----	-----	-----	v, 58	-----
Doppler satellite tracking	-----	-----	-----	-----	-----	182
Downward emission (see Longwave emission)						
Downward solar radiative flux	-----	32	-----	-----	-----	-----
Downwelling of oceans	148, 150, 156	158	-----	-----	103, 109, 115, 116, 123, 136, 154	275
Drag coefficient	-----	68	-----	-----	-----	-----
Drainage basins	-----	-----	-----	197	25, 26, 27	-----
Drift ice duration	-----	-----	122	-----	-----	-----
Drinking water supply (see also Water resources)	-----	-----	-----	-----	37	-----
Drought	132, 191	9	157	18, 127, 175, 177, 206	19, 30, 40-42, 52, 59, 71, 77, 81, 150, 155, 165, 212, 213, 217	-----
1976-77 California areas of recurrent carbon dioxide relationships with cyclical character of frequency and duration of health effects of	-----	-----	-----	-----	42	-----
	-----	-----	-----	-----	42	-----
	-----	-----	-----	-----	30	-----
	-----	-----	-----	-----	41	-----
	-----	-----	-----	-----	41, 42, 80	-----
	-----	-----	-----	-----	42, 189	-----
Drought-adapted varieties	-----	-----	-----	197, 199, 201	-----	-----
Drought and wet periods: patterns of	-----	-----	xxvi, xxvii, 158	-----	-----	-----
Drought signature	-----	-----	155	-----	-----	-----
Drought stress	-----	-----	-----	63, 193, 194, 195, 199	-----	-----
Drought tolerance	-----	-----	-----	127, 189, 198	150	-----

Dry basins

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Dry basins	-----	-----	-----	-----	35	-----
Dry extraction	28	-----	-----	-----	-----	-----
Dry matter of plants	-----	-----	-----	55, 67, 68, 119, 120	-----	-----
Dry-matter partitioning in plants	-----	-----	-----	37, 66, 67, 68, 69, 113, 207	-----	-----
Dry-matter production	-----	-----	-----	158	-----	-----
Dry-weight gain	-----	-----	-----	55, 63, 67, 74, 76, 80, 83, 158, 159, 195, 198, 199	-----	-----
Drying of the soil	-----	99, 103, 104, 132, 271	-----	-----	-----	-----
Dryness: seasonal	-----	-----	-----	-----	74	-----
Dryness belt	-----	-----	-----	-----	74	-----
Duke University	129	-----	-----	-----	-----	-----
Duke University Phytotron	-----	-----	-----	18, 21, 27	-----	-----
Dungeness crab	-----	-----	-----	-----	98	-----
Dust	-----	44, 45, 48, 167, 268, 269, 326	-----	-----	-----	-----
stratospheric	50	-----	-----	-----	-----	-----
Dust as a site of bacterial growth	-----	-----	-----	-----	190	-----
Dust storms	-----	-----	-----	-----	80	-----
Dust veil index	-----	-----	42, 83	-----	-----	-----
Dust veils	-----	167, 168, 171, 186	-----	-----	-----	-----
Dye-3 Borehole	-----	-----	-----	-----	25	-----
Dynamical feedback	-----	205, 210-211, 213	-----	-----	-----	-----
DYNUMES	-----	-----	-----	-----	139	-----
Dysentery	-----	-----	-----	-----	178, 193	-----

E

Earhart Laboratory for Plant Research	-----	-----	-----	13	-----	-----
Earth:	-----	-----	-----	-----	-----	-----
axis of rotation of crust of	-----	-----	96, 172	-----	-----	73
180, 194	-----	-----	-----	-----	-----	-----
energy-balance components of the	-----	6, 7	-----	-----	-----	-----
inclination of axis of mantle of the:	-----	252	-----	-----	-----	-----
flow of rock within	-----	-----	-----	-----	-----	34, 328
moment of inertia of	-----	-----	96	-----	-----	-----
orbital parameters of	-----	64, 202, 240	4, 6, 134	-----	-----	-----
orbital variations of	-----	16, 18, 247	-----	-----	-----	-----
radiation balance of	-----	-----	xviii, 167, 182, 183	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Earth (continued)						
radiation budget or energy balance of	-----	xviii, 27, 40, 41, 310, 313	-----	-----	-----	-----
rotation of the (see also Planetary rotation; Rotational response)	-----	-----	-----	-----	-----	3, 34, 61, 68, 93, 94, 97-101, 143
axis of (see also Polar wander)	-----	-----	-----	-----	-----	93
rotation rate of surface energy balance of topography of	-----	64	-----	-----	-----	220
Earth radiation budget satellite	-----	-----	47	-----	-----	-----
East Antarctic flow	-----	-----	-----	-----	-----	185
East Antarctic Ice Sheet	-----	-----	111	-----	-----	8, 46, 56, 183, 301
East Antarctic input	-----	-----	-----	-----	-----	185-186
East Antarctic outlet glacier: outflow from	-----	-----	-----	-----	-----	31
East Germany	-----	-----	-----	-----	34	-----
East Greenland Current	-----	-----	122	-----	-----	-----
Eastern hemlock	-----	-----	-----	-----	148	-----
Eclipse records	-----	-----	-----	-----	-----	34, 101
Ecological responses (see also Whole plant ...)	-----	-----	-----	6	-----	-----
Economic development	xx, 71, 77, 237, 240, 266	-----	-----	-----	36	-----
Economic factors	-----	-----	-----	-----	xvii, 97-99	-----
Economic Research Service	-----	-----	-----	-----	91	-----
Economic stagnation: global	47	-----	-----	-----	-----	-----
Economic yield	-----	-----	-----	55	-----	-----
Economic zones: exclusive	-----	-----	-----	-----	99	-----
Economics: effects on cropping patterns of	-----	-----	-----	-----	85	-----
Ecosystem migration	202, 263	-----	-----	-----	-----	-----
Ecosystem respiration	-----	-----	-----	136, 137	-----	-----
Ecosystem responses (see also Carbon dioxide concentration effects)	21	-----	-----	ix, xvii, 7, 146	-----	-----
Ecosystem studies: natural	-----	-----	-----	xxii, xxiv, 7, 13, 24, 101, 119, 133, 145, 147, 207, 209	-----	-----
Ecosystem succession: theories of	257, 294, 295	-----	-----	-----	-----	-----

Ecosystem types

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ecosystem types	-----	-----	-----	146	-----	-----
Ecosystems	-----	-----	-----	-----	161	-----
<aquatic (see="" a="" also="" fisheries)<=""></aquatic>	-----	-----	-----	-----	19	-----
distributions of	-----	-----	-----	-----	25, 35, 40, 43, 55, 100	-----
disturbed	xix, 63, 170, 257, 263	-----	-----	-----	-----	-----
forest	-----	-----	-----	-----	40, 151, 153, 154-157, 158, 160, 161	-----
undisturbed	143	-----	-----	-----	-----	-----
unmanaged	-----	-----	-----	-----	31	-----
Ecotypic differences in carbon dioxide response	-----	-----	-----	132	-----	-----
Eddies	-----	-----	-----	-----	102	-----
large scale synoptic	71	-----	-----	-----	-----	-----
mesoscale	84	72	-----	-----	-----	-----
small scale turbulent	-----	67	-----	-----	-----	-----
transient	-----	179	-----	-----	-----	-----
Eddy correlation systems	201	-----	-----	-----	-----	-----
Eddy diffusion coefficient	148	-----	-----	-----	-----	-----
Eddy diffusivity	152	-----	-----	-----	-----	-----
vertical deep ocean	-----	172, 179	-----	-----	-----	-----
Eddy diffusivity profiles	-----	-----	-----	24	-----	-----
Egg code	-----	-----	122	-----	-----	-----
EGIG profile	-----	-----	-----	-----	-----	27, 43, 256, 261
Egypt	-----	-----	-----	-----	178	-----
Eigenfunctions	-----	-----	-----	-----	-----	76-77, 78, 83, 84, 87, 88, 89
Ekman divergence	-----	-----	125	-----	-----	-----
El Chichon	48, 50, 51	44, 182, 193, 199, 213	70, 73, 84	-----	-----	-----
El Niño	-----	-----	70, 94	-----	-----	-----
definition	-----	182, 184	-----	-----	-----	-----
fishing yield decline from	-----	-----	-----	-----	98, 108, 127, 139	-----
El Niño/Southern Oscillation	xx, 5, 19, 38, 45, 47, 49-53, 57, 95, 133, 168, 191, 258, 295, 298	5, 279	71, 84	-----	108, 216	74
ELCROS	-----	-----	-----	45	-----	-----
Eldgja, Iceland	-----	-----	44	-----	-----	-----
Electric Power Research Institute	241, 242	-----	-----	-----	-----	-----
Electricity:	-----	-----	-----	-----	-----	-----
tropospheric	-----	202	-----	-----	-----	-----
Electricity use	71	-----	-----	-----	-----	-----
Electrification	192	-----	-----	-----	-----	-----
Electron transport capacity	-----	-----	-----	123	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
ELM	-----	-----	-----	43	-----	-----
Emission rates of chemically active gases	-----	217	-----	-----	-----	-----
Emissions:						
carbon dioxide	65-72, 227, 229, 230, 258, 274	-----	-----	-----	-----	-----
distribution of future	292	-----	-----	-----	-----	-----
fossil fuel carbon dioxide	292-293, 297-298	-----	-----	-----	-----	-----
xvii, 66-71, 218-220, 231, 254, 255, 258-262, 270, 281	-----	-----	-----	-----	-----	-----
Emissivity	-----	34, 88, 113, 306, 307, 316	-----	-----	-----	-----
Empirical methods for estimating climate change	-----	19, 64	-----	-----	-----	-----
Empirical orthogonal function (EOF)	49	-----	154-155	-----	-----	17
Encephalitis	-----	-----	-----	-----	193	-----
End-product inhibition	-----	-----	-----	58, 126, 127, 132, 141-142	-----	-----
Endemicity:						
mapping of	-----	-----	-----	-----	201	-----
Enderby Land Glaciers	-----	-----	-----	-----	-----	173
Energy and climate	240	-----	-----	-----	-----	-----
Energy balance:						
components of	-----	-----	-----	-----	-----	249, 255
Energy balance models	-----	13, 84-85, 141, 153, 161, 173, 265, 267, 283-289, 340, 350, 354, 359	-----	-----	-----	-----
limitations of planetary	-----	85, 290	-----	-----	-----	-----
surface	-----	84, 87, 266, 283, 289	-----	-----	-----	-----
thermodynamic zonally averaged	-----	84, 266, 283, 285-289, 323, 324	-----	-----	-----	-----
153, 267	-----	-----	-----	-----	-----	-----
268	-----	-----	-----	-----	-----	-----
Energy budgets of oceans and atmosphere	-----	-----	xix, 151, 175	-----	-----	-----
Energy conservation	79	-----	-----	-----	-----	-----
Energy consumption:						
growth of	-----	-----	-----	v	-----	-----
growth rate of	-----	v, 217	v	-----	-----	-----
Energy costs	-----	-----	-----	-----	72	-----
Energy demand	224	-----	-----	-----	-----	-----
future	xx, 11, 71, 79	-----	-----	-----	-----	-----
income elasticity of	226, 243, 292	-----	-----	-----	-----	-----
Energy efficiency	xxi, 224, 237, 243, 292	-----	-----	-----	-----	-----
Energy exchanges	3	262	-----	-----	-----	-----

Energy fluxes

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Energy fluxes: glacial	-----	-----	-----	-----	-----	251, 255
Energy fluxes from human activities	-----	203	-----	-----	-----	-----
Energy growth: future	-----	223	-----	-----	-----	-----
Energy labor substitution	243	-----	-----	-----	-----	-----
Energy park: definition	-----	214	-----	-----	-----	-----
Energy production: projections of	240	-----	-----	-----	-----	-----
Energy productivity	224	-----	-----	-----	-----	-----
Energy resources	73-77	-----	-----	-----	-----	-----
Energy sources: benign	278, 282	-----	-----	-----	-----	-----
<i>Energy Statistics Yearbook</i>	65-66	-----	-----	-----	-----	-----
Energy storage	79	-----	-----	-----	-----	-----
Energy transfer processes	-----	261, 277	-----	-----	-----	-----
Engabreen Glacier	-----	-----	-----	-----	-----	35, 223
Enhanced oil recovery	74	-----	-----	-----	-----	-----
<i>Environment of West Antarctica, Potential CO₂-Induced Changes</i>	-----	-----	-----	-----	-----	10, 46
Environmental limits on plant response	-----	-----	-----	56, 146	-----	-----
Environmental Protection Agency	241, 242	-----	-----	14, 24	34	-----
Environmental stress	-----	-----	-----	119	-----	-----
Enzyme damage	-----	-----	-----	73	-----	-----
Enzyme kinetics	-----	-----	-----	174	-----	-----
Enzyme levels	-----	-----	-----	141	-----	-----
Enzyme reaction rates in fish	-----	-----	-----	-----	105	-----
Enzymes (see also Ribulose bisphosphate)	-----	-----	-----	58	-----	-----
Eocene Period	300	-----	-----	-----	-----	-----
EOF analysis	-----	-----	154-155	-----	-----	-----
Epidermal cells	-----	-----	-----	69	-----	-----
Epipelagic species	-----	-----	-----	-----	105	-----
Episodic oceanic events: short term	104	-----	-----	-----	-----	-----
Epstein-Barr virus	-----	-----	-----	-----	183	-----
Equation of mass continuity	-----	66-67	-----	-----	-----	-----
Equations: dynamical	-----	66-67	-----	-----	-----	-----
Equator	-----	-----	-----	-----	109	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Equatorial regions	41, 48, 84, 95	-----	-----	-----	-----	-----
Equilibration time: ocean-atmosphere	156	-----	-----	-----	-----	-----
Equilibrium climate: change in	-----	171, 266, 327	-----	-----	-----	-----
Equilibrium constants	85	-----	-----	-----	-----	-----
Equilibrium line altitude of: changes of	-----	-----	-----	-----	-----	150, 217, 250-257
definition elevation of the glacial ablation	-----	-----	-----	-----	-----	43, 250, 251, 253, 255-257, 258, 261, 265
Equilibrium temperature	-----	154, 156, 158, 169	-----	-----	-----	159, 255
Erosion	122, 184, 299	-----	-----	xxv, 77, 193, 200, 201	43, 79-80, 99, 212, 214	-----
control of effects of vegetative cover on	-----	-----	-----	-----	44, 80	-----
effects of water on	-----	-----	-----	-----	79	-----
effects of wind on	-----	-----	-----	-----	80	-----
susceptibility to	-----	-----	-----	-----	80	-----
ERS-1 satellite	-----	-----	-----	-----	-----	36
Escherichia coli	-----	-----	-----	-----	190	-----
Estimates: discrepancies in limitations of	117, 249, 250, 294-128	-----	-----	-----	-----	-----
Estimates of reserves and resources	73-77	-----	-----	-----	-----	-----
Estrous cycle of humans: climatological influences on	-----	-----	-----	-----	177	-----
Estuaries	-----	-----	-----	-----	127, 128, 137, 139, 213	-----
Estuarine systems	xix, 96	-----	-----	-----	-----	-----
Ethylene	293	-----	-----	-----	-----	-----
Eucaryotes	194, 203	-----	-----	-----	-----	-----
Euphotic zone	-----	-----	-----	-----	109	-----
Eurasia	-----	129	119, 120, 121, 130, 132, 160	-----	-----	-----
snow cover changes in	-----	-----	-----	-----	-----	38, 39
Europe	294	99, 130, 132, 244	38, 41, 102, 112, 117, 120, 126, 155-156	-----	34	87-89
glacier retreat in	-----	-----	-----	-----	-----	frontispiece, 217-218, 224
Eustasy: global	-----	-----	-----	-----	-----	90
Eustatic changes: definition	-----	-----	-----	-----	-----	12

Eustatic sea level

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Eustatic sea level variations of	-----	-----	-----	-----	-----	327 59, 92-102
Eustatic signals	-----	-----	-----	-----	-----	86
Eutrophication	9, 97, 203	-----	-----	-----	32	-----
Evaporation	-----	7, 43, 61, 93, 103, 261, 270, 285	-----	-----	27-28	124, 138
definition	-----	-----	-----	-----	27	-----
rates of	-----	95, 262, 271, 333	-----	-----	-----	-----
reservoir surface	-----	-----	-----	-----	27	-----
soil	-----	-----	-----	-----	35, 74, 214	-----
reduction of	-----	-----	-----	-----	83	-----
Evaporation from bare soils	-----	-----	-----	-----	27	-----
Evaporation from free water surfaces	-----	-----	-----	-----	27	-----
Evaporation of soil water	-----	-----	-----	64, 76, 77	-----	-----
Evaporation reduction methods	-----	-----	-----	-----	39, 83	-----
Evaporative cooling	-----	132-133	-----	-----	-----	-----
Evaporative losses	-----	-----	-----	-----	39, 52	-----
Evapotranspiration	119	204, 216	-----	xxv, 38, 63, 64, 81, 83, 193, 197, 198, 199, 201	40, 59, 212	-----
Exchanges:						
carbon reservoir:						
dynamics of	9	-----	-----	-----	-----	40-45, 46-58, 62-64
land-ice and ocean	-----	-----	-----	-----	-----	-----
Exclusive economic zones	-----	-----	-----	-----	99	-----
Exogenic cycle	184	-----	-----	-----	-----	-----
Exotic species: importation of	294	-----	-----	-----	-----	-----
Experiments: agricultural	-----	-----	-----	-----	88	-----
Export (see Translocation)						
Exports of agricultural products	-----	-----	-----	-----	71	-----
Extension services	-----	-----	-----	-----	73	-----
External forcing	-----	163, 242-243, 267, 284	4, 9, 10	-----	-----	-----
Extrapolation errors	-----	-----	-----	139	-----	-----
Extratropical rain belt	-----	103	-----	-----	-----	-----
Extreme events (weather)	-----	-----	-----	-----	xv, 29, 42, 55, 189-190	-----
drainage basin response to frequency of	-----	xxv, 3, 11, 75, 278, 279	-----	-----	30 30, 129	-----
Exudation (see Root exudation)						

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
F						
Faba bean	-----	-----	-----	75, 133	-----	-----
Factors:						
disaggregation of	258	-----	-----	-----	-----	-----
Faeroe-Shetland Channel	-----	-----	-----	-----	-----	133-134
Falkland Islands	40	-----	-----	-----	-----	-----
Fallowing	-----	-----	-----	-----	81	-----
Famine	-----	-----	-----	-----	71	-----
Farm management factors	-----	-----	-----	193	-----	-----
Farm policy:						
national	-----	-----	-----	-----	xvii, 88	-----
Farm population	-----	-----	-----	-----	72	-----
Farm production						
stability of in the United States	-----	-----	-----	-----	42	-----
-----	-----	-----	-----	-----	86	-----
Farm structures for animals	-----	-----	-----	-----	78	-----
Fatty acids:						
chloroplast synthesis of	-----	-----	-----	134	-----	-----
Federal Republic of Germany	229, 242	-----	42	-----	34	-----
Federation of Astronomical and Geophysical Sciences	-----	-----	-----	-----	-----	216
Feed:						
animal	-----	-----	-----	-----	72	-----
Feedback	xxii, 9, 21, 32, 145, 199, 200, 204, 205, 254, 282, 293, 299	-----	-----	-----	-----	-----
albedo	-----	xxv, 154, 155, 162, 358	-----	-----	-----	-----
analysis of	-----	84, 137-138, 223, 284	-----	-----	-----	-----
atmosphere-ocean	-----	182	-----	-----	-----	-----
cloud	-----	ix, xxv, 16, 50, 88, 89, 137, 141, 143, 155, 215, 222, 276, 302, 316, 350, 359	-----	-----	-----	-----
cloud-altitude	-----	88, 89, 138, 302-305, 316, 317	-----	-----	-----	-----
definition	-----	15, 357	-----	-----	-----	-----
dynamical	-----	205, 210-211, 213	-----	-----	-----	-----
ice-albedo	-----	89, 91, 102, 107, 123, 215, 222, 313, 314, 317, 355, 356	-----	-----	-----	-----
lapse-rate	-----	88, 89, 138, 296, 300, 301, 313, 317	-----	-----	-----	-----
moist adiabatic lapse rate	-----	88, 91, 316	-----	-----	-----	-----

Feedback

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Feedback (continued)						
nonlinear		183				
optical depth feedback		310-313, 315, 316, 317				
quantitative evaluations of		84				
snow-albedo definition		107				
surface-albedo		16, 65, 102				
		88, 89, 144, 313-315, 316, 317				
temperature lapse rate		299				
temperature/radiation		262, 286, 287				
temperature/sensible heat		288				
temperature/water-vapor: definition		15-16				
water-vapor		297, 298, 299, 309, 315, 317, 330, 355				
water-vapor/evaporation		288				
water-vapor/solar radiation		287				
water-vapor/temperature		65, 88, 89, 107, 141, 155				
Feedback effects	103-104, 263					
Feedback inhibition				43, 57, 91, 121, 128		
Feedback mechanisms						56, 281, 327
Feedback processes		64-65, 266, 271, 275-276, 284, 295, 339	xxviii, 5, 7		3, 12	
atmospheric characteristics of		xx, xxv, 15, 164				
		ix, 64-65, 284-287, 359				
definition		63				
Feedback responses: ecosystem level					28, 35	
Feedback sensitivity		357-358				
Female hormones: temperature influences on					176	
Fennoscandia						76, 83, 94, 99
Fennoscandian Ice Sheet						2, 15, 59, 93
Fertilization	57					
Fertilization effect	54, 96					
Fertilization of forest stands					149	
Fertilizer				xxi, 21, 81, 190, 191, 200	72	
costs of				191		
Fertilizer denitrification		197				
Fescue					79	
Festuca				161		
Field environment				14, 21, 84		

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Field studies:						
fish	-----	-----	-----	-----	133, 137	-----
Fields:						
old	-----	-----	-----	160	-----	-----
Filchner-Ronne Ice Shelf (Ronne-Filchner Ice Shelf)	-----	-----	-----	-----	-----	31, 46, 57, 197, 198, 199, 203-204, 275, 280, 301, 302, 303, 305, 309, 314, 315, 325
thickness of	-----	-----	-----	-----	-----	32
Fingerprint strategy	-----	-----	7, 9, 10, 82, 167, 174, 175, 180, 184	-----	-----	-----
Finite element analyses of ice shelves	-----	-----	-----	-----	-----	57, 279, 287, 289, 292
Finland	-----	-----	130	-----	-----	-----
Fire cycles	-----	-----	-----	138	-----	-----
Fires	xx, 119, 126, 127, 143, 146, 177, 191, 197, 202, 257, 297	-----	-----	-----	151, 165, 213	-----
Firn:						
refreezing within the	-----	-----	-----	-----	-----	25, 43, 44, 63, 159
Firn line:						
position of the	-----	-----	-----	-----	-----	235, 319
First Global Geophysical Experiment	92	-----	-----	-----	-----	-----
Fish (see also Spawning):						
biogeographic distribution patterns of	-----	-----	-----	-----	105, 119, 122	-----
biological transition zones of	-----	-----	-----	-----	111	-----
captive breeding and rearing of	-----	-----	-----	-----	99	-----
commercial ranges of	-----	-----	-----	-----	119, 122	-----
competition among demersal	-----	-----	-----	-----	131	-----
economically important	-----	-----	-----	-----	98, 118, 124	-----
global yield of	-----	-----	-----	-----	97	-----
growth rates of	-----	-----	-----	-----	99	-----
intertidal spawning of	-----	-----	-----	-----	97, 105, 119, 133	-----
lag time in detection of reproductive success of	-----	-----	-----	-----	128	-----
life cycle stages of	-----	-----	-----	-----	110	-----
life history of	-----	-----	-----	-----	105, 109, 118, 125, 129, 134, 135	-----
life span of	-----	-----	-----	-----	106	-----
low egg production by	-----	-----	-----	-----	106	-----
metabolic losses of	-----	-----	-----	-----	110	-----
metabolic rates of	-----	-----	-----	-----	108	-----
parasites of	-----	-----	-----	-----	105	-----
pelagic	-----	-----	-----	-----	105, 125, 131, 132, 134, 140	-----
					106, 124	-----

Fish

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Fish (continued)						
physiological tolerance limits of	-----	-----	-----	-----	111	-----
population crashes of	-----	-----	-----	-----	113, 216	-----
population fluctuations and lifespans of	-----	-----	-----	-----	113	-----
population increases of predators of	-----	-----	-----	-----	108 107, 118, 120, 124, 125	-----
reduced catches of reproduction of	-----	-----	-----	-----	98	-----
sensitivity to pH and trace metals of	-----	-----	-----	-----	109, 113, 123, 130	-----
starvation of transitional environments of	-----	-----	-----	-----	130, 133 124	-----
year class strength of	-----	-----	-----	-----	109, 130, 133, 135	-----
Fish abundance	-----	-----	-----	-----	107, 110, 125, 130-132, 134	-----
driving forces of environmental factors of match/mismatch hypothesis of	-----	-----	-----	-----	108	-----
mechanisms controlling nursery layer stability hypothesis of	-----	-----	-----	-----	100, 113-125, 137	-----
transport hypothesis of	-----	-----	-----	-----	110, 118	-----
Fish biomass production	-----	-----	-----	-----	97	-----
Fish egg mortality	-----	-----	-----	-----	123	-----
effects of turbulence on	-----	-----	-----	-----	108	-----
Fish eggs and larvae: survival of	-----	-----	-----	-----	101, 111, 123, 137	-----
Fish habitat	-----	-----	-----	-----	103, 106, 111	-----
Fish migration patterns	-----	-----	-----	-----	99, 105, 106, 108, 109, 118, 120, 124	-----
Fish mortality rates of	-----	-----	-----	-----	105, 110, 120 109, 123, 130, 133, 134, 135	-----
Fish populations:						
age structure of	-----	-----	-----	-----	109	-----
recoveries of	-----	-----	-----	-----	110	-----
sampling methods for	-----	-----	-----	-----	130	-----
Fish prey	-----	-----	-----	-----	107, 133	-----
Fish production:						
abiotic factors	-----	-----	-----	-----	100, 139	-----
Fish runs	-----	-----	-----	-----	37	-----
Fish spawning	-----	-----	-----	-----	105, 106, 107, 119, 120, 123	-----
seasonal abundance of prey and	-----	-----	-----	-----	110, 123	-----
Fish species ranges	-----	-----	-----	-----	105, 119	-----
Fish survival:						
interacting impacts on	-----	-----	-----	-----	103, 133	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Fish trade	-----	-----	-----	-----	98	-----
Fisheries	-----	-----	-----	-----	xiv, xv, xvii, 6, 97-140, 212-218, 220, 221	-----
catch restrictions on cohort abundance of current research programs in	-----	-----	-----	-----	99	-----
depth residence of economic significance of effects of carbon dioxide on	-----	-----	-----	-----	123	-----
effects of salinity changes on	-----	-----	-----	-----	138	-----
effects of temperature increases on	-----	-----	-----	-----	105	-----
environmental factors of freshwater	-----	-----	-----	-----	97-99	-----
global	-----	-----	-----	-----	97-140	-----
human nutrition and near shore region of open-ocean	-----	-----	-----	-----	99-111	-----
response to climate change of upwelling warm-water	-----	-----	-----	-----	127	-----
Fisheries data inadequacy of	-----	-----	-----	-----	111, 125-128	-----
Fisheries Oceanography Experiment (FOX)	-----	-----	-----	-----	173, 195	-----
Fishery-climate relationships	-----	-----	-----	-----	114	-----
Fishery management: nonclimatic factors in	-----	-----	-----	-----	127	-----
Fishery products: demand for uses of	-----	-----	-----	-----	6, 37, 97-140, 212-218, 220	-----
Fishery research: environmental factors in	-----	-----	-----	-----	109, 127, 137	-----
Fishery resources: management of	-----	-----	-----	-----	127, 137	-----
Fishery species	-----	-----	-----	-----	xvii, 130-132	-----
Fishery yields	-----	-----	-----	-----	128	-----
Fishery zones	-----	-----	-----	-----	137, 138	-----
Fishing pressures	-----	-----	-----	-----	111, 125, 130-132	-----
Flagellates: motile	-----	-----	-----	-----	110	-----
Fisheries	-----	-----	-----	-----	99	-----
Fishery products: demand for uses of	-----	-----	-----	-----	99, 195	-----
Fishery research: environmental factors in	-----	-----	-----	-----	97	-----
Fishery resources: management of	-----	-----	-----	-----	110	-----
Fishery species	-----	-----	-----	-----	99	-----
Fishery yields	-----	-----	-----	-----	44, 98, 99, 105, 106-107, 108, 109, 110, 112, 113, 118, 119, 120-121, 123-124, 125, 127, 128, 129, 139, 140	-----
Fishery zones	-----	-----	-----	-----	97, 108, 109, 111, 123, 124, 127	-----
Fishing pressures	-----	-----	-----	-----	126	-----
Flagellates: motile	-----	-----	-----	-----	124	-----
Fisheries	-----	-----	-----	-----	116	-----

Flask sampling

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Flask sampling	40-57	-----	-----	-----	-----	-----
Flatfishes	-----	-----	-----	-----	107, 125	-----
Floats: submerged	84	-----	-----	-----	-----	-----
Floe size	-----	-----	122, 124	-----	-----	-----
Flood control	-----	-----	-----	-----	43	-----
Flooding	-----	-----	116	177	29, 30, 42-43, 51-52, 59, 62, 71, 156, 165, 212, 213, 215, 217	-----
carbon dioxide relationships with causes of effects of health effects of	-----	-----	-----	-----	30, 42	-----
Floodplains regulation of	-----	-----	-----	-----	42, 43	-----
Flow: impediment of inactive solifluxion	-----	-----	-----	-----	43	-----
Flow directions	-----	-----	-----	-----	43	-----
Flow distribution: time dependence of glacial	-----	-----	-----	-----	205	-----
Flow dynamics	-----	-----	-----	-----	45, 235, 316	-----
Flow in stably stratified ocean basins	-----	178	-----	-----	-----	-----
Flow law	-----	-----	-----	-----	293, 297	-----
Flowering: effects of carbon dioxide concentration on timing of	-----	-----	-----	161	-----	-----
Flowers: quality of quantity of weight of	-----	-----	-----	xxiii, 39, 63, 70, 86, 127, 131, 134, 160, 208	-----	-----
Fluorocarbon dating	56	-----	-----	-----	-----	-----
Fluorocarbons (see Chlorofluorocarbons)	-----	-----	-----	71	-----	-----
Fluxes: biologically mediated	296	-----	-----	-----	-----	-----
Food and Agricultural Organization	19, 116, 121, 123, 124, 133	-----	-----	-----	-----	-----
Food production	-----	-----	-----	x, 3, 90, 130	71	-----
Food supply agricultural: variation of fish: partitioning of	3	-----	-----	-----	71	-----
	-----	-----	-----	-----	131	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Food supply						
fish (continued)						
pelagic detritus	-----	-----	-----	-----	121	-----
fisheries:						
variation of	-----	-----	-----	-----	108, 124, 133, 139, 140	-----
societal stability and	-----	-----	-----	-----	71	-----
Food supply and demand: worldwide	-----	-----	-----	191, 196	-----	-----
Foodweb:						
interactions in pelagic-benthic partitioning in	-----	-----	-----	-----	103, 136 101	-----
Forage	-----	-----	-----	-----	72, 213, 215, 217, 218	-----
genetic improvements in management of quality of	-----	-----	-----	-----	77	-----
warm weather risks in research on:	-----	-----	-----	140, 148	-----	-----
economic considerations of species of	-----	-----	-----	-----	79	-----
vulnerability of to climate variability	-----	-----	-----	-----	75-77, 79, 85, 90	-----
-----	-----	-----	-----	-----	76	-----
Forbs:						
short grass	-----	-----	-----	166	-----	-----
Forcing functions	223-227, 243	-----	-----	-----	-----	-----
definition	223	-----	-----	-----	-----	-----
Forcing mechanisms	-----	xviii, 164-169, 261, 324	-----	-----	-----	-----
Forest cultivars	-----	-----	-----	79	-----	-----
Forest ecosystems	-----	-----	-----	-----	40, 151, 153, 154-157, 158, 160, 161	-----
Forest-prairie boundary	-----	-----	-----	-----	153, 164	-----
Forest products:						
substitutes for	-----	-----	-----	-----	221	-----
Forest products industry	-----	-----	-----	-----	19, 147, 149, 158	-----
Forest species	-----	-----	-----	-----	147, 148, 161	-----
Forest stands:						
dynamic equilibrium	-----	-----	-----	-----	158	-----
Forestry practices	-----	-----	-----	187	-----	-----
Forests (see also Trees)	8, 21, 115, 123, 199, 202, 251, 264, 266-267, 294	-----	-----	-----	xv, xvii, 6, 18, 147-164, 212-218, 220, 221	-----
boreal	117, 122, 264, 265	-----	-----	135	-----	-----
boundaries of	-----	-----	-----	-----	159	-----
burning of	127, 133	-----	-----	-----	-----	-----
carbon storage or release by	-----	-----	-----	-----	151, 158, 162	-----
clearing of (see also Deforestation)	9, 11, 19, 22, 121, 124, 144-145, 147,	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Fossil fuel mix	224	-----	-----	-----	-----	-----
Fossil fuel production: definition	65	-----	-----	-----	-----	-----
Fossil fuel releases	xvii, 6, 7, 9, 20, 52, 65-72, 159, 238, 255, 275	-----	-----	-----	-----	-----
errors in forecasts of	250 231-236, 237, 239-242, 249, 259, 277, 281	-----	-----	-----	-----	-----
historical seasonality of uncertainties in	250, 292 54, 131 xxi, 221-223, 239, 240, 242, 250, 255, 274	-----	-----	-----	-----	-----
Fossil fuel use	11, 57, 131, 145, 147, 163, 218, 230, 291, 297	-----	-----	-----	-----	-----
controls on decline of projections of temperature and	12 47 11, 65-78, 217 3	-----	-----	-----	-----	-----
Fossil fuels burning of	-----	-----	-----	-----	11 v, 3, 11, 163	-----
	v, xv, 4, 5, 9, 18, 34, 37, 45, 47, 65-78, 102, 177, 202, 217, 249, 263, 295	v, xxiv, 17, 163, v 164, 167, 169, 196, 197, 261, 264, 268	-----	v, xi, 75, 179, 181, 209	-----	-----
consumption of	-----	83, 151, 153, 163, 168, 174	-----	-----	-----	-----
cost of demand for	77, 226 237	-----	-----	-----	-----	-----
effects of increased costs of on agriculture	-----	-----	-----	-----	84	-----
global production and consumption of	38, 50, 65-72, 78	-----	-----	-----	-----	-----
restraints on use of	11, 76-77, 228	-----	-----	-----	-----	-----
Foundation Ice Stream	-----	-----	-----	-----	-----	306
Fourier heat conduction law	-----	157	-----	-----	-----	-----
Fourier transform infrared spectroscopy	58	-----	-----	-----	-----	-----
Foxtail	-----	-----	-----	131, 158	-----	-----
Free-air carbon dioxide enrichment (FACE)	-----	-----	-----	xix, 14, 23-25, 26, 27, 28	-----	-----
Free-air field releases	-----	-----	-----	14, 23, 28, 83, 121	-----	-----
costs of	-----	-----	-----	23	-----	-----
Free rider problem	228	-----	-----	-----	-----	-----
Freezes: subtropical United States unseasonal	-----	-----	-----	-----	75 71	-----
Freezeup and breakup: decadal variability in	-----	-----	130	-----	-----	-----
French Ministry of Agriculture	-----	-----	-----	14, 25	-----	-----

Freons

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Freons (see Chlorofluorocarbons)						
Freshwater ice	-----	-----	129-130, 138	-----	-----	-----
data coverage of	-----	-----	130	-----	-----	-----
effects on climate of	-----	-----	130	-----	-----	-----
freezeup and breakup	-----	-----	129	-----	-----	-----
processes of	-----	-----	114, 129	-----	-----	-----
interannual variability of	-----	-----	114, 129	-----	-----	-----
Freshwater input (see also Deep water, freshening of; Meltwater; Sea water, freshening of)	-----	-----	-----	-----	20, 22, 34	-----
Freshwater input to coastal waters	-----	-----	-----	-----	112, 116, 128	-----
Frictional force at the Earth's surface	-----	68	-----	-----	-----	-----
Frost	-----	-----	-----	76, 134	-----	-----
Frostbite	-----	-----	-----	-----	175	-----
Fruit	-----	-----	-----	67, 71	-----	-----
dry weight of	-----	-----	-----	71, 83	-----	-----
scarring of	-----	-----	-----	77	-----	-----
size of	-----	-----	-----	71, 188	-----	-----
weight of	-----	-----	-----	71, 160	-----	-----
Fruiting: timing of	-----	-----	-----	xxiii, 39, 70, 86, 134	-----	-----
Fuel: carbon content of	65	-----	-----	-----	-----	-----
Fuel data:						
global	66, 68	-----	-----	-----	-----	-----
People's Republic of China	78	-----	-----	-----	-----	-----
uncertainties in	65, 68, 78	-----	-----	-----	-----	-----
Union of Soviet Socialist Republics	78	-----	-----	-----	-----	-----
Fuel mix: impact of	71, 237, 261, 262	-----	-----	-----	-----	-----
Fuel prices	226, 227	-----	-----	-----	-----	-----
Fuel shortages	72	-----	-----	-----	-----	-----
Fuelwood production	-----	-----	-----	-----	147	-----
Fumaroles	184, 202	-----	-----	-----	-----	-----
Fungal infections	-----	-----	-----	-----	84, 199	-----
airborne	-----	-----	-----	-----	190-192	-----
meteorological factors in	-----	-----	-----	-----	191-192	-----
Furrowing	-----	-----	-----	-----	81-82	-----
G						
Gadid family	-----	-----	-----	-----	113, 125	-----
Gadoids	-----	-----	-----	-----	108	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
<i>Gadus morhua</i>	-----	-----	-----	-----	108	-----
Gaia hypothesis	205, 254, 258, 262, 300	-----	-----	-----	-----	-----
Gas chromatography	28	-----	-----	-----	-----	-----
Gas exchange processes of rate of	150, 169 91	-----	-----	17, 46	-----	-----
Gas exchange system: leaf	-----	-----	-----	17-18	-----	-----
Gas Research Institute	241, 242	-----	-----	-----	-----	-----
Gaseous absorption	-----	33-36	-----	-----	-----	-----
Gases: radiative properties of	-----	33	-----	-----	-----	-----
Gastroenteritis	-----	-----	-----	-----	178	-----
General circulation models (see also Models, general circulation)	3 -----	13, 36, 50, 70-71, 73-75, 76, 89-138, 141-144, 162, 184, 215, 242, 253, 264, 265-266, 326, 340, 342, 354, 355 170	-----	-----	14, 60, 139, 153, 162 40, 48, 62, 63, 314	-----
asynchronously coupled atmosphere-ocean equilibrium response of range of variability in	-----	176 175	-----	-----	-----	-----
Generic plant response	-----	-----	-----	104	-----	-----
Genetic base in grain crops: narrowing of	-----	-----	-----	-----	76	-----
Genetic differentiation	-----	-----	-----	45	-----	-----
Genetic engineering	-----	-----	-----	xxiv, 189, 198, 200, 201	-----	-----
Genetic improvements in crops and animals	-----	-----	-----	-----	xviii, 72, 75-77, 87, 89, 175, 216	-----
Genetic selection: human	-----	-----	-----	-----	177	-----
Genetic techniques of fish breeding	-----	-----	-----	-----	99	-----
Geochemical history	203	-----	-----	-----	-----	-----
Geochemical Ocean Sections	19, 90, 91, 93-94, 99-101, 105, 150, 152, 153, 157, 169, 170, 204, 296	-----	-----	-----	-----	-----
Geochemical processes	32, 195, 196	-----	-----	-----	-----	-----
Geodetic control	-----	-----	-----	-----	-----	28
Geologic evidence	-----	-----	4	-----	-----	319
Geologic fluxes	195	-----	-----	-----	-----	-----
Geologic record	203, 282, 293	-----	-----	-----	-----	-----
Geologic smoothing	191	-----	-----	-----	-----	-----

Geological records

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Geological records	-----	xxiii, 8, 59, 64, 240	-----	-----	-----	-----
Geological Survey of Greenland	-----	-----	-----	-----	-----	156, 158
Geomorphological changes	-----	-----	-----	-----	57	-----
Geophysical Fluid Dynamics Laboratory	-----	156, 175	-----	-----	-----	-----
Geophysical Monitoring for Climate Change Program	19, 37, 40-44	-----	-----	-----	-----	-----
George VI Ice Shelf	-----	-----	-----	-----	-----	4, 31, 51, 203, 204, 302, 309-310
forward velocity of ice front position of	-----	-----	-----	-----	-----	201
-----	-----	-----	-----	-----	-----	199-201
George VI Sound	-----	-----	-----	-----	-----	202-203
GEOS	-----	-----	-----	-----	-----	235, 237
GEOSECS	-----	179, 186	-----	-----	-----	129, 135
Geosphere	177	-----	-----	-----	11	-----
Germany	229, 242	-----	42	-----	34	-----
Gilman Glacier	-----	-----	-----	-----	-----	146, 150
Glacial (see also Glaciers)	-----	-----	-----	-----	-----	-----
Glacial ablation formula	-----	-----	136	-----	-----	-----
Glacial advance and retreat	-----	-----	134, 173	-----	-----	-----
Glacial history	-----	-----	-----	-----	-----	145-146
Glacial-interglacial carbon dioxide change: effects of	-----	240	-----	-----	-----	-----
Glacial-interglacial cycles	xvi, 27, 34, 56, 188, 190, 191, 299	-----	115	-----	-----	-----
Glacial maximum	-----	-----	112	-----	-----	-----
Glacial postglacial shifts in carbon dioxide	-----	-----	115	-----	-----	-----
Glacial rebound	-----	-----	-----	-----	-----	73, 76, 83
Glacial recession: hydrologic effects of	-----	-----	xxiv, 133	-----	-----	-----
Glaciation	-----	64	-----	-----	-----	-----
Late Wisconsinan	-----	-----	-----	-----	80	-----
Glacier balances geographic distribution of	-----	-----	-----	-----	-----	140
-----	-----	-----	-----	-----	-----	139
Glacier behavior: forecasting future	-----	-----	-----	-----	-----	220
Glacier tongues advance and retreat of	-----	-----	-----	-----	-----	217
-----	-----	-----	-----	-----	-----	220, 222
Glaciers (see also Ice caps; Ice sheets; Ice streams; Snow and ice) advance of areal changes of	102, 181, 186, 199, 202	61, 72, 163	xxviii, 133-138, 171, 173, 174	-----	-----	23-25
-----	-----	-----	-----	-----	-----	139
-----	-----	-----	-----	-----	-----	147-149, 232, 237

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Glaciers (continued)						
cirque						217
classification of						145, 216, 220, 221, 225, 228
continental						221
debris of						226, 227
definition						145
effect of climate on mass			135-136			
balance of						
effects of on sea level						
effects of rising						4, 5, 23-25, 36, 43, 60, 64, 220, 237
temperature on						42, 62-63, 216
effects on climate of			134			
elevations of:						
median						219
energy balance of						248-253
enhanced melting of						303, 306-309
flow dynamics of						45, 235, 316
flow lines of:						
velocity profiles of						207, 294-295
fluctuations of			133			139, 220
fluxes from						192, 249
heat sources for melting of						119-121
iceberg discharge from						3, 33, 67, 161-163, 210-215, 249, 265, 308
length of						217, 224
history of						224-225
locations of						22, 139
maritime						221
mass balance histories of						139, 141
mass balance of (see also						2, 35, 61, 139, 141, 145-154, 181-185, 190, 198-199, 204,
Mass balance)						217, 223, 228, 248
measurement of						67, 142, 147-150, 155, 160, 162, 164-167, 168, 222, 232
relationship to elevation of						159
time series of:						
reconstruction of						220-222, 228
variations of						207, 222, 224
mass balances and volume			134, 139			
changes of						
measurement of						37, 232, 234, 236
melting of	192		xxiii, 137, 172			118-119, 140, 303
rates of						21, 28, 44, 121, 122, 124, 150, 202, 308, 309-310
monitoring of						220-228, 233-237
mountain						8, 34-36, 226
outlet						145, 178, 185, 311, 316
photogrammatic						frontispiece, 150, 168
measurements of						216, 248-253, 297
response of to						
carbon-dioxide-induced						
climate change						

Glaciers

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Glaciers (continued)						
response time of response to climatic fluctuations of retreat of	-----	-----	134	-----	-----	187, 232
rates of simulated sizes of: distribution of small surface elevations of surging	-----	-----	-----	-----	-----	7, 31, 139, 149, 162, 197, 207, 217, 228
survey methods for Swiss Alp	-----	-----	-----	-----	-----	55, 264, 266 282-285
thickness of: changes in	-----	-----	-----	-----	-----	227
topographic maps of transitional or subcontinental types of	-----	-----	-----	-----	-----	1, 41-43, 93 162, 164-165, 168
velocity of	-----	-----	-----	-----	-----	315
volume of (see also Glaciers and ice caps, total volume of the world's)	-----	-----	-----	-----	-----	150
volumetric changes of wastage or growth of	-----	-----	-----	-----	-----	217
						149-150, 207, 223, 235, 237
						235
						222
						145, 216, 220, 221, 225, 228
						207, 235
						139, 140, 144
						237
						1, 2, 3, 4, 62, 139, 140, 143, 144, 152, 207, 253
Glaciers and ice caps:						
contribution to sea level of (see also Glaciers, effects of on sea level)	-----	-----	-----	-----	-----	23-25
total volume of the world's (see also Glaciers, volume of)	-----	-----	-----	-----	-----	43
Glaciers and ice sheets:						
projections of discharge rates of	-----	-----	-----	-----	-----	6
Glaciologic evidence	-----	-----	-----	-----	-----	178-209
Glaciologic studies	-----	-----	-----	-----	-----	36
Glasshouse experiments	21	-----	-----	-----	-----	-----
Global Atmospheric Aerosol and Radiation Study	-----	38	-----	-----	-----	-----
Global average surface temperatures (see Surface air temperature, global)						
Global carbon budget	-----	-----	-----	-----	137	-----
Global carbon cycle	v, xv, xix, 3, 4-9, 17, 21, 22, 33, 36, 47, 50, 55, 74, 77, 83-85, 115, 130, 143-171, 177-206, 280	v	vi	3, 35, 101, 173, 176, 181, 210	v, 11, 139, 150, 163, 197	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Global carbon cycle (continued)				vi	-----	-----
definition	-----	-----	-----	vi	-----	-----
Global climate computerized data base of	-----	-----	-----	-----	v 153	-----
Global energy balance	-----	vi, xvii, 27, 65, 153, 261, 265	-----	-----	-----	-----
Global hydrologic cycle	-----	-----	-----	-----	25	-----
Global mean surface air temperatures (see Surface air temperature, global)						
Global Positioning Satellite	-----	-----	-----	-----	-----	237
Global warming (see also Temperature changes)	-----	-----	-----	35	13, 14, 173	-----
GLYCIM	-----	-----	-----	41, 42, 43, 80	-----	-----
Goddard Institute for Space Studies	-----	216	114, 129	-----	-----	-----
Government programs: agricultural	-----	-----	-----	-----	71-72	-----
Gradients: seasonal	19	-----	-----	-----	-----	-----
spatial	19	-----	-----	-----	-----	-----
Grain amaranth	-----	-----	-----	-----	85	-----
Grain production: North American world	-----	-----	-----	-----	77-79, 85, 86, 88 42	-----
Grand Banks	-----	-----	-----	-----	-----	131, 133-134, 135
Grapes	-----	-----	-----	87	-----	-----
Grasses: cool season	-----	-----	-----	-----	79	-----
desert	-----	-----	-----	121	-----	-----
warm season	-----	-----	-----	-----	85, 90	-----
Grasslands	122, 199, 200	-----	-----	45, 135, 181	-----	-----
California serpentine prairie	-----	-----	-----	161	-----	-----
-----	-----	-----	-----	14, 24	-----	-----
Gräsubreen Glacier	-----	-----	-----	-----	-----	35, 223
Gravity waves	-----	68	-----	-----	-----	-----
Grazing	199, 201	-----	-----	-----	-----	-----
Great Plains	-----	-----	120	-----	-----	-----
Green revolution	-----	-----	-----	-----	72	-----
Greenhouse effect	xv, 3, 135, 205, 242, 243	xviii, 48, 65, 83, 88, 152, 154, 163, 168, 170, 205, 206, 208, 209, 211, 221, 270, 287, 316, 327, 348	4, 181	6	13	-----
definition	-----	28	-----	-----	-----	-----
Greenhouse experiments	-----	-----	-----	-----	150, 151	-----
Greenhouse gases	-----	152, 163, 165, 184	16, 23, 26	-----	-----	-----
definition	-----	28	-----	-----	-----	-----

Greenhouses

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Greenhouses	-----	-----	-----	xi, xix, 14, 21, 26, 27, 28, 55, 63, 147, 188	-----	-----
carbon-dioxide-enriched	-----	-----	-----	xviii, xix, 3, 27	-----	-----
Greenland	32, 33, 56	-----	111-112, 126, 133, 173	-----	-----	161
mass loss from	-----	-----	-----	-----	-----	67, 97
Greenland Ice Cap	-----	8	-----	-----	-----	98, 258-266
mass balance of	-----	-----	-----	-----	-----	258
Greenland ice cores	-----	-----	44, 64	-----	-----	-----
Greenland Ice Sheet	-----	-----	132, 134, 135	-----	-----	1, 2, 3, 8, 26, 27, 28, 43-45, 60-61, 63-64, 68, 160, 165, 167, 255-257
ablation of	-----	-----	-----	-----	-----	28, 40, 43
elevation changes of	-----	-----	-----	-----	-----	60
imbalances of the	-----	-----	-----	-----	-----	166
mass balance of	-----	-----	-----	-----	-----	12, 25, 43, 61, 68, 155-171, 259
melting of	-----	-----	-----	-----	-----	5, 43, 156
volume of the	-----	-----	-----	-----	-----	155
Greenland Sea	20, 94	-----	-----	-----	-----	135
Grenz horizons	198	-----	-----	-----	-----	-----
Grid release system	-----	-----	-----	14	-----	-----
Grindelwald Glacier	-----	-----	-----	-----	-----	224
Gross national product	xxi, 226, 230, 237, 258	-----	-----	-----	-----	-----
Gross primary production	118, 177, 186	-----	-----	121, 136, 137, 173	-----	-----
Ground ice (see also Permafrost)	-----	-----	130-133, 138, 139	-----	-----	-----
Ground ice time response of	-----	-----	-----	-----	-----	232
Grounded ice: Antarctic: area of	-----	-----	-----	-----	-----	198
Grounding lines	-----	-----	-----	-----	-----	52, 53, 56, 180, 188, 204, 208, 305, 313, 318
advance of	-----	-----	-----	-----	-----	199, 318, 321
backpressure at	-----	-----	-----	-----	-----	57, 322, 327
discharge velocities of	-----	-----	-----	-----	-----	320-324
marine ice sheet	-----	-----	-----	-----	-----	78, 178
retreat of	-----	-----	-----	-----	-----	53, 56, 199, 206, 280, 283, 317, 320-325, 326
shift of	-----	-----	-----	-----	-----	296-299
stability of	-----	-----	-----	-----	-----	8, 53, 55
strain rates at	-----	-----	-----	-----	-----	327
thinning of	-----	-----	-----	-----	-----	281
Groundwater	-----	-----	-----	-----	26	-----
contamination of	-----	-----	-----	-----	32	-----
legal status of	-----	-----	-----	-----	36	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Groundwater infiltration into sewerage systems	-----	-----	-----	-----	32	-----
Groundwater management code	-----	-----	-----	-----	37	-----
Groundwater management practices	-----	-----	-----	-----	36	-----
Groundwater mining	-----	-----	-----	-----	31, 35-36, 52, 59, 82, 212, 213, 217	-----
nonclimatic determinants of temperature effects on	-----	-----	-----	-----	36-37	-----
Groundwater pumping capacity	-----	-----	-----	-----	36, 50	-----
Groundwater quality	-----	-----	-----	-----	36	-----
Groundwater recharge: artificial natural	-----	-----	-----	-----	37, 213, 217 31	-----
Groundwater systems: dynamic equilibrium	-----	-----	-----	-----	31	-----
Growing areas: shifts in	-----	-----	-----	192, 193, 195, 196, 197, 199-200, 201	-----	-----
Growing degree days	-----	-----	-----	-----	78, 153	-----
Growing season	-----	-----	-----	67, 76, 196	-----	-----
Growing season length	-----	-----	-----	-----	75, 212	-----
GROWL	-----	-----	-----	45	-----	-----
Growth analysis	-----	-----	-----	36, 157, 168	-----	-----
Growth chambers	-----	-----	-----	xviii, xix, xx, 13, 14, 18, 27, 55, 82, 83, 188	-----	-----
Growth enhancement	-----	-----	-----	ix, xi, xvii, xxiii, 13, 167, 181, 182	-----	-----
limitations on	-----	-----	-----	55, 82	-----	-----
Growth forms	-----	-----	-----	123, 145, 146, 212	-----	-----
Growth rates: leaf	-----	-----	-----	43, 68-70, 113, 128-129	-----	-----
plant	-----	-----	-----	xxi, 5, 67, 127-132, 182	-----	-----
absolute and relative initial	-----	-----	-----	69, 129, 162, 167 147	-----	-----
Gulf of Alaska	-----	-----	126	-----	111, 112	2, 23, 60, 67, 143
Gulf of Finland	-----	-----	-----	-----	-----	86
Gulf of Maine	-----	-----	-----	-----	106	-----
Gulf Stream	-----	-----	-----	-----	125	-----
Gulkana Glacier	-----	-----	-----	-----	-----	35, 223
Gyres midlatitude	84	-----	185	-----	-----	-----

Habitats

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
H						
Habitats:						
fish	-----	-----	-----	-----	100, 139	-----
nursery					123	
loss of wildlife	-----	-----	-----	-----	40	-----
parasite and insect-vector	-----	-----	-----	-----	175	-----
plant	-----	-----	-----	145, 212	-----	-----
virgin	-----	-----	-----	-----	124	-----
Hadley cells	-----	-----	157	-----	-----	-----
Hadley circulation:						
definition	-----	9	-----	-----	-----	-----
Hailstorms	-----	-----	-----	-----	71	-----
Halibut	-----	-----	-----	-----	107, 110, 123	-----
Halocline	-----	-----	-----	-----	102	-----
Hardwoods	-----	-----	-----	160	147	-----
Harvest index	-----	-----	-----	71, 90, 103, 104, 105-109, 112, 114, 175, 188, 193, 200, 207, 220, 227, 235, 240, 255, 268	-----	-----
Hawaii to Tahiti Shuttle Experiment	92, 95, 105	-----	-----	-----	-----	-----
Hay	-----	-----	-----	-----	76	-----
Hay fever	-----	-----	-----	-----	192	-----
Health Council of the Netherlands	-----	-----	-----	181	-----	-----
Health effects	-----	-----	-----	7	-----	-----
Health monitoring techniques	-----	-----	-----	-----	201	-----
Heart disease	-----	-----	-----	-----	178-181	-----
Heart disease mortality and meteorological variables	-----	-----	-----	-----	180, 181	-----
Heat:						
effects of on elderly	-----	-----	-----	-----	176	-----
poleward transport of	-----	72, 161, 265	-----	-----	-----	-----
vertical transport in atmosphere	-----	99, 156, 222	-----	-----	-----	-----
Heat and moisture fluxes	-----	-----	112	-----	-----	-----
Heat balance:						
measurements of	-----	-----	-----	-----	43	-----
Heat capacity of the atmosphere	-----	6	-----	-----	-----	-----
Heat capacity of the land surface	-----	7, 160, 162, 175, 268	-----	-----	-----	-----
Heat capacity of the ocean	-----	162, 175, 268	-----	-----	-----	-----
Heat content of the climate system	-----	-----	75	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Heat edema	-----	-----	-----	-----	175	-----
Heat flux	-----	62, 67, 159-160	-----	-----	-----	-----
Heat flux:						
ocean-atmosphere	-----	-----	96	-----	-----	-----
oceanic	-----	-----	113	-----	-----	-----
oceanic mixed layer	-----	179	-----	-----	-----	-----
Heat stresses on crops	-----	-----	-----	-----	77	-----
Heat stresses on humans	-----	-----	-----	-----	176, 189	-----
Heat stroke	-----	-----	-----	-----	175, 189, 198	-----
Heat tolerance of animals	-----	-----	-----	-----	76	-----
Heat transfer	-----	-----	-----	-----	-----	123, 124
ocean-to-ice	-----	-----	-----	-----	-----	4, 66, 124
deep-ocean	-----	171	-----	-----	-----	-----
Heat transport:						
vertical and horizontal in oceans	-----	-----	-----	-----	102	-----
Heat transport to the deep ocean	-----	171	xxvi	-----	-----	-----
Heat waves	-----	-----	-----	-----	184-189, 216	-----
characteristics of	-----	-----	-----	-----	165, 189, 198	-----
effects on death rates of	-----	-----	-----	-----	185-189, 198	-----
Heavy metals	266	-----	-----	-----	-----	-----
Helium-3	91, 156	-----	-----	-----	-----	-----
Hemispheric asymmetry	-----	162, 177	-----	-----	-----	-----
Henry Ice Rise	-----	-----	-----	-----	-----	31, 302, 305, 306, 315
Herbicides	-----	-----	-----	192, 200	44, 72	-----
Herbivores	199, 200	-----	-----	-----	-----	-----
carbon stored by	199	-----	-----	-----	-----	-----
Herbivory	200, 263	-----	-----	xxii, 102, 119, 128, 135, 140, 148, 169, 192, 199, 200, 201, 208, 210, 212	-----	-----
Herring	-----	-----	-----	-----	106-107, 108, 112, 119, 120-121, 123, 124, 129, 139	-----
Heterotrophes	181, 186, 187, 199, 204, 264, 298	-----	-----	-----	-----	-----
Heterotrophic pools	186	-----	-----	-----	-----	-----
Hickory	-----	-----	-----	162	-----	-----
High-altitude-balloon observations	-----	39	-----	-----	-----	-----
High Plains Study Council	-----	-----	-----	-----	82	-----
High salinity shelf water	-----	-----	-----	-----	-----	117-119
salinity and volume of	-----	-----	-----	-----	-----	121, 124
Himalayas	-----	-----	119	-----	-----	-----

Histoplasmosis

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Histoplasmosis	-----	-----	-----	-----	191	-----
Historical assessments	129, 203	-----	-----	-----	-----	-----
Historical impacts	18	-----	-----	-----	-----	-----
Histosols	117, 181	-----	-----	-----	-----	-----
Hodges Glacier	-----	-----	-----	-----	-----	207
Hokkaido, Japan	-----	-----	126	-----	-----	-----
Holdridge Classification System	-----	-----	-----	-----	153, 159, 160	-----
Holdridge life zone	116, 118, 265	-----	-----	-----	-----	-----
Holocene Epoch	181, 187, 251	17, 239, 241, 246, 269	-----	-----	-----	-----
Holocoenosis	-----	-----	-----	5	-----	-----
Homeostasis	205, 300	-----	-----	-----	-----	-----
Homeostatic mechanisms	-----	-----	-----	37, 120, 145	-----	-----
Homicides: seasonal variation in	-----	-----	-----	-----	184	-----
Hookworm: climate sensitivity of	-----	-----	-----	-----	194	-----
Host-pest relationships	-----	-----	-----	xxv, 192, 201	-----	-----
Hot springs	184	-----	-----	-----	-----	-----
Hudson Bay	-----	-----	121	-----	-----	-----
Human activities: impacts of	v, 10, 20, 35, 37-54, 122, 134,	v, xvii, xix, 62, 168, 193-199, 143, 180, 201, 201, 203, 223, 203, 251, 277, 279 282, 297, 300	v, 165	-----	v, 3, 11	12
 intensity in a watershed of	-----	-----	-----	-----	62	-----
Human biochemistry and physiology: changes in seasonal variations in	-----	-----	-----	-----	173, 175 177, 199, 212	-----
Human carrier diseases: meteorological factors in	-----	-----	-----	-----	173, 193	-----
Human disturbances	-----	-----	-----	v, 173, 181	-----	-----
Human health (see also Diseases, human)	-----	-----	-----	-----	xv, 6, 173-202, 212-218, 220, 221	-----
Human health: effects of drought on effects of temperature increases on meteorological effects on nonmeteorological effects on water resources and	-----	-----	-----	-----	42 179, 184-189, 198 xviii, 173-202 173, 184-189, 199, 216 175, 195	-----
Human health care: technological advances in	-----	-----	-----	-----	221	-----
Human hormone levels: temperature influences on	-----	-----	-----	-----	176	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Human life: prolongation of	-----	-----	-----	-----	184	-----
Human population: increases of	-----	194, 264	-----	-----	-----	-----
Human settlement changes	-----	-----	-----	-----	57	-----
Human welfare	-----	-----	-----	-----	ix, 3, 4	-----
Humid regions water-managed strategies for	-----	-----	-----	-----	34 81	-----
Humidity (see also Relative humidity)	-----	51, 63, 222, 230	-----	xviii, 18, 66, 126, 207	xiv, xv, 198-200, 214 175	-----
modification of temperature effects by tropospheric	-----	-----	183	-----	-----	-----
Humidity control	-----	-----	-----	60	-----	-----
Humus	115, 181, 186, 198, 200, 202	-----	-----	-----	28, 80	-----
Hurricanes: health effects of	-----	-----	-----	-----	189	-----
Hurst Coefficient	-----	-----	-----	-----	52, 58	-----
Hurst Effect	-----	-----	-----	-----	41	-----
Hydrilla	-----	-----	-----	-----	39	-----
Hydroelectric power generation	-----	-----	-----	-----	37	-----
Hydrogen ion concentration	85	-----	-----	-----	-----	-----
Hydrogen-3	99, 156, 169	-----	-----	-----	-----	-----
Hydrographic casts: distribution of	-----	-----	98	-----	-----	-----
Hydrographic data collection of time series of	-----	-----	97	-----	134, 135	104
Hydrographic surveys	-----	-----	104	-----	-----	-----
Hydrologic balance	-----	-----	93, 100	-----	-----	110
Hydrologic balances: simulation of	-----	74	-----	-----	-----	-----
Hydrologic budget	-----	-----	-----	-----	-----	25, 155-162, 167-168
Hydrologic cycle	4, 262	50, 61, 102-103, 130-137	114, 151, 171, 173	-----	25-31	12, 232
changes in	-----	48, 98	-----	-----	-----	-----
Hydrologic equilibrium: equation of	-----	-----	-----	-----	25-26	-----
Hydrologic processes	-----	-----	-----	197	60	-----
Hydrologic records: length of	-----	-----	-----	-----	58, 62	-----
Hydrologic regime alteration	4	-----	-----	-----	-----	-----
Hydrologic systems continuity of mass of	-----	-----	-----	-----	25, 26, 55-57 25-27	-----

Hydrologic systems

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Hydrologic systems (continued)						
effects of vegetative canopy on	-----	-----	-----	-----	31, 55-57	-----
linkages with vegetation and climate of outputs of:	-----	-----	-----	-----	27-29	-----
unknowns in response rate to climate change of	-----	-----	-----	-----	56	-----
storage changes in	-----	-----	-----	-----	31	-----
Hydrology surface	-----	xxii, 62	-----	-----	26	-----
Hydrosphere definition	204, 299	61	-----	-----	28	-----
Hydrostatic equation	-----	60, 63	-----	-----	-----	-----
Hydroxyl radical	-----	67	-----	-----	-----	-----
Hypsithermal definition	-----	207, 268-269	-----	-----	145	-----
Hypsithermal definition	-----	17-18, 249	-----	-----	16, 241, 250	-----

I

Ice (see also Snow and ice; Sea ice; Global ice volume)	-----	-----	111, 114	-----	-----	-----
Ice:						
age distribution of	-----	-----	137	-----	-----	-----
age of	-----	-----	124	-----	-----	-----
floating:						
normal stress in	-----	-----	-----	-----	289	-----
gas bubbles in	21, 28, 31, 36,	-----	-----	-----	11	-----
56	-----	-----	-----	-----	-----	-----
glacial	10, 177, 188	-----	-----	-----	-----	-----
global volume of	-----	250	-----	-----	-----	-----
grounded	-----	-----	-----	-----	178, 180	-----
heat flux through	-----	-----	113	-----	-----	-----
lateral diffusion and	-----	-----	125	-----	-----	-----
advection of	-----	-----	-----	-----	-----	-----
melting of land-locked	-----	-----	96	-----	-----	-----
ratio of Pleistocene to	-----	-----	-----	-----	63	-----
Holocene	-----	-----	-----	-----	-----	-----
redistribution of	-----	-----	-----	-----	50, 124	-----
temperature indices and	-----	-----	130	-----	-----	-----
formation of	-----	-----	-----	-----	124	-----
transport of	-----	-----	-----	-----	34, 64, 253	-----
wastage of	-----	-----	-----	-----	-----	-----
Ice advance	-----	-----	125	-----	-----	-----
Ice Age (see also Little Ice Age)	-----	-----	-----	-----	-----	-----
Ice Age, Last	-----	-----	-----	-----	145	-----
Ice age cycle	-----	-----	-----	-----	99	-----
Ice ages	184	64, 357	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ice albedo feedback	-----	89, 91, 102, 107, 123, 215, 222, 314, 317, 355, 356	-----	-----	-----	-----
definition	-----	313	-----	-----	-----	-----
Ice and water load (see also Mass load of the planet): rates of change of	-----	-----	-----	-----	-----	102
Ice anomalies	-----	-----	-----	-----	-----	39
Ice area: Earth's	-----	-----	-----	-----	-----	12
Ice caps	-----	-----	-----	-----	-----	146, 152
accumulation rates of	-----	-----	-----	-----	-----	23
dynamic	-----	-----	-----	-----	-----	145
flowlines of:	-----	-----	-----	-----	-----	259
diagrams of	-----	-----	-----	-----	-----	3, 62
growth of	-----	-----	-----	-----	-----	23-25, 61, 139
mass balance of	-----	-----	-----	-----	-----	23, 25
melt rates of	-----	-----	-----	-----	-----	232-237
monitoring of	-----	-----	-----	-----	-----	262
response times of	-----	-----	-----	-----	-----	25, 263, 266
thinning or thickening of	-----	-----	-----	-----	-----	5, 25, 64
warming of	-----	-----	-----	-----	-----	143
wastage of	-----	-----	-----	-----	-----	-----
Ice-core record	v, xv, xvii, xxiii, 29, 33, 156, 190 35-37, 55, 56, 130, 191, 252, 275, 282, 291, 295, 298, 299	v, 194, 240	vi, 3, 44, 83	vi	-----	9, 23, 139, 145,
Ice cover	-----	-----	-----	-----	102, 105, 111, 113, 118, 119, 124, 125, 127, 128, 130, 131, 132, 135, 139, 212	-----
Earth's	-----	-----	-----	-----	-----	34
barrier to predators	-----	-----	-----	-----	105, 120	-----
provided by	-----	-----	-----	-----	-----	-----
Ice discharge (see also Ice drainage)	-----	-----	-----	-----	-----	55, 64, 185, 301, 306-309, 310, 311, 312
Ice divides: equilibrium thickness of	-----	-----	-----	-----	-----	53
Ice drainage system: Antarctic (see also Ice discharge)	-----	-----	-----	-----	-----	301, 304, 311, 315
Ice dynamic equations	-----	-----	-----	-----	-----	265
Ice dynamics	-----	-----	125	-----	-----	-----
Ice-edge retreat	-----	314	-----	-----	-----	-----
Ice extent	-----	-----	-----	-----	101, 102, 111, 114, 126, 129, 133, 139, 140, 213	-----
Ice features	-----	-----	-----	-----	-----	47
Ice flow	-----	-----	-----	-----	-----	180, 181, 208, 225, 264

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ice flow (continued)						
effects of basal temperature on measurements of velocities of	-----	-----	-----	-----	-----	52
Ice fronts: movement of	-----	-----	-----	-----	-----	197, 199-201, 313
Ice mass: changes in disintegration of	-----	-----	-----	-----	-----	206 33, 34, 52, 94, 97-101, 206
Ice melt	-----	-----	95-96, 101, 104, 172	-----	-----	1, 4, 143, 256, 305
Ice melting: climate change and estimates of	-----	-----	-----	-----	-----	309-313 10
Ice pump	-----	-----	-----	-----	-----	50, 275-278
Ice ramps: retreat of	-----	-----	-----	-----	-----	204
Ice rises: flotation of grounded importance of shear stresses in	-----	-----	-----	-----	-----	305-306 208, 301 305 57
Ice ripples: definition	-----	-----	-----	-----	-----	306
Ice sheets (see also Ice shelves; Ice streams)	200	xxi, xxii, 59, 61, 72, 162, 163, 248	133-139, 171	-----	-----	-----
ablation of predictions of	-----	-----	-----	-----	-----	206
ablation rates of	-----	-----	-----	-----	-----	40
accumulation rates of	-----	-----	-----	-----	-----	3, 7
bottom melting of	-----	-----	-----	-----	-----	3, 7, 308
disintegration of	-----	-----	-----	-----	-----	7
dynamics of	-----	-----	115	-----	-----	94, 97-101 33, 178, 280, 301-315
effects on climate of	-----	-----	134-137	-----	-----	-----
elevation of	-----	-----	-----	-----	-----	237
extent of	-----	-----	-----	-----	-----	280
growth or decay of (see also Ice sheets, thinning or thickening of)	-----	-----	134	-----	-----	-----
history of retreat of	-----	-----	-----	-----	-----	188
interactions with atmosphere of	-----	-----	115	-----	-----	-----
marine	-----	-----	-----	-----	-----	8, 9, 280
instability of	-----	-----	-----	-----	-----	8, 47
mass balance of	-----	-----	-----	-----	-----	2, 121, 123, 125, 155-171
observations of	-----	-----	-----	-----	-----	222
measurement of	-----	-----	-----	-----	-----	233, 237
melting of	-----	-----	xxiii	-----	-----	41, 54, 311, 312
modeling of	-----	-----	-----	-----	-----	51, 301-315
modeling shrinkage of	-----	-----	-----	-----	-----	53-58
monitoring of	-----	-----	-----	-----	-----	232-237, 315
Pleistocene	-----	-----	-----	-----	-----	3, 12, 14, 25-28,

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ice sheets (continued)	-----	-----	-----	-----	-----	61
redistribution of mass during melting of	-----	-----	-----	-----	-----	93
response to climate change of	-----	-----	-----	-----	-----	4, 45, 301-315
stabilizing of	-----	-----	-----	-----	-----	178, 280
thinning or thickening of (see also Ice sheets, growth or decay of)	-----	-----	-----	-----	-----	28, 162, 168, 313
topography of warm cores of	-----	-----	-----	-----	-----	314 119-121
Ice shelf fronts: melting of	-----	-----	-----	-----	-----	277
Ice shelf/seawater interface	-----	-----	-----	-----	-----	278
Ice shelf water	-----	-----	-----	-----	-----	118-119
Ice shelves (see also Ice sheets; Ice streams)	-----	-----	135	-----	-----	4, 21, 145, 146, 208, 276
Ice shelves:	-----	-----	-----	-----	-----	-----
accumulation on	-----	-----	-----	-----	-----	184, 186
arching and bending of	-----	-----	-----	-----	-----	288
basal melting of (see also Basal melting)	-----	-----	-----	-----	-----	30, 31, 47, 61, 62, 63, 172, 186, 201, 208, 308, 314
buttressing of	-----	-----	-----	-----	-----	280, 281, 282, 285
calving of	-----	-----	-----	-----	-----	4
characteristics of	-----	-----	-----	-----	-----	315
circulation beneath	-----	-----	-----	-----	-----	66, 122-124, 125
climatic limit of	-----	-----	-----	-----	-----	197
creep of	-----	-----	-----	-----	-----	303, 305, 308
equations for	-----	-----	-----	-----	-----	306
dynamics of	-----	-----	-----	-----	-----	303-305, 319
effects of climate change on	-----	-----	-----	-----	-----	305
floating	-----	-----	-----	-----	-----	302
flow directions of	-----	-----	-----	-----	-----	183
freezing rate of	-----	-----	-----	-----	-----	201
heat transfer to	-----	-----	-----	-----	-----	4
interaction of with ice streams	-----	-----	-----	-----	-----	4, 54-56, 63, 303
margins of (see also Iceberg calving fronts)	-----	-----	-----	-----	-----	3, 5, 198
changes in	-----	-----	-----	-----	-----	3
mapping of	-----	-----	-----	-----	-----	36, 235
mass balance of	-----	-----	-----	-----	-----	30, 122, 185
melting of (see also Ice melt)	-----	-----	-----	-----	-----	4, 275-278, 306-309, 316
modeling of	-----	-----	-----	-----	-----	53
movement of	-----	-----	-----	-----	-----	30
properties of the sea under	-----	-----	-----	-----	-----	201
rates of melting	-----	-----	-----	-----	-----	3, 203
response to	-----	-----	-----	-----	-----	48, 54
carbon-dioxide-induced climate change	-----	-----	-----	-----	-----	-----
seaward boundary of (see Ice shelves, margins of)	-----	-----	-----	-----	-----	30
strain rate of	-----	-----	-----	-----	-----	57, 279
stress distribution in	-----	-----	-----	-----	-----	-----

Ice shelves

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ice shelves (continued)						
surface melting of	-----	-----	-----	-----	-----	47, 184, 187, 310, 314
thickening rates of	-----	-----	-----	-----	-----	30, 31, 34, 57, 183, 184, 187, 303, 305
thinning of	-----	-----	-----	-----	-----	4, 47, 63, 187, 303, 305-306, 311, 317, 319
Ice sliding law	-----	-----	-----	-----	-----	52
Ice/snow albedo feedback	-----	-----	-----	-----	-----	41
Ice storms:						
effects on forests of	-----	-----	-----	-----	165	-----
Ice streams	-----	-----	-----	-----	-----	5, 53, 67, 178, 208
acceleration of	-----	-----	-----	-----	-----	63, 303
discharge of	-----	-----	-----	-----	-----	53, 308
drainage rates of	-----	-----	-----	-----	-----	305
dynamics of	-----	-----	-----	-----	-----	51, 63, 67
flow of	-----	-----	-----	-----	-----	33
modeling of	-----	-----	-----	-----	-----	51-58
formation of	-----	-----	-----	-----	-----	52, 279, 280, 295-299
interaction of with ice shelves	-----	-----	-----	-----	-----	4, 54-56, 63, 303
stabilization of	-----	-----	-----	-----	-----	319
stress in	-----	-----	-----	-----	-----	315
surface elevation of	-----	-----	-----	-----	-----	315
thickness of	-----	-----	-----	-----	-----	57, 315
velocity of	-----	-----	-----	-----	-----	52, 200-201, 208, 303, 305, 308, 315
water beneath	-----	-----	-----	-----	-----	51
Ice surface temperature	-----	-----	124	-----	-----	-----
Ice thickness	-----	-----	-----	-----	-----	180, 185
maps of	-----	-----	-----	-----	-----	173, 174, 180, 181
Ice thickness profiles	-----	-----	-----	-----	-----	124, 168, 308
Ice velocities:						
calculation of	-----	-----	-----	-----	-----	52
observation of	-----	-----	-----	-----	-----	56, 173-176
Ice volume	-----	-----	131, 134, 139	-----	-----	-----
calculation of	-----	-----	-----	-----	-----	68
fluctuations in	-----	-----	-----	-----	-----	99, 205, 208
Iceberg calving	-----	-----	xxiv, 134, 136	-----	-----	3, 8, 9, 33, 54, 56, 60, 61, 67, 125, 161, 162, 163, 208, 210-215, 265, 281, 285, 289, 302, 306-310, 311, 312, 313, 314, 316
climatic warming and	-----	-----	-----	-----	-----	302-303, 309-313
driving force for	-----	-----	-----	-----	-----	285
effects of basal melting	-----	-----	-----	-----	-----	322
on	-----	-----	-----	-----	-----	
effects of increased	-----	-----	-----	-----	-----	265, 303

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Iceberg calving (continued)						
mechanisms of rate of						57, 63, 279, 291 5, 210, 260, 265, 284, 308
Antarctic						21, 33-34, 215
Iceberg calving flux						161, 262
Iceberg calving fronts						57
effect of on grounding lines						323
Iceberg calving process: finite-element analysis of						280
Iceberg discharge						3, 8, 9, 33, 54, 56, 60, 61, 67, 125, 161, 162, 163, 208, 210-215, 235, 265, 281, 285, 289, 302, 306-310, 311, 312, 313, 314, 316
Iceberg monitoring			136			
Icebergs						121-122
calculated volumes of						213
data set on						210-215
decay of						122
drift of						122
half-life of						214
life expectancy of						33, 214
movement of						121, 125
populations of						213, 315
thickness of						122
total in the Southern Ocean						33, 213
Iceland			122			141
Iceland drift ice			64			
Iceland-Scotland overflow						131, 133-134
Icemelt						105, 114, 116, 124
IIASA scenario	230, 240, 279					
Incident solar flux (see Solar irradiance)						
Inclinometer measurements in deep boreholes						167, 168
India		129, 131, 248, 249, 252	34, 121, 156, 160		43	
Indian Ocean	53, 91, 93	247				116
Indicators of climate change			xxiv, 172			
Indirect effects: definition				187	vii, ix, xiii, 3, 174	
Indirect effects of a carbon dioxide-induced climate change				3, 7		

Industrial activity

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Industrial activity	-----	-----	45	-----	-----	-----
Industrialization	xvi, 65, 71, 79, 177, 293	3, 168, 193, 199, 203	-----	-----	-----	-----
nutrients or toxins from	131	-----	-----	-----	-----	-----
Infiltration: definition	-----	-----	-----	-----	28	-----
Infiltration of soil	-----	-----	-----	-----	26	-----
Infiltration rates of soil effects of plant species composition on	-----	-----	-----	-----	36	-----
Inflection line: ice stream: definition	-----	-----	-----	-----	28	-----
Influenza: seasonal variation in	-----	-----	-----	-----	181	-----
Information exchange	17	-----	-----	-----	-----	-----
Infrared (see also Longwave)	-----	-----	-----	14	-----	-----
Infrared radiation (see Longwave radiation)	-----	-----	-----	-----	-----	-----
Infrared spectroscopy	27, 28, 36	-----	-----	-----	-----	-----
Injection: deep water	257	-----	-----	-----	-----	-----
Inland ice: buildup of	-----	-----	-----	-----	-----	188
Inland Ice Sheet: changes in the	-----	-----	-----	-----	-----	319-321
Inorganic carbon: dissolved (see also Inorganic carbon, total dissolved)	85, 105, 152	-----	-----	-----	-----	-----
global flux from rivers of oceanic	95	-----	-----	-----	-----	-----
terrestrial	188	-----	-----	-----	-----	-----
total dissolved	8	-----	-----	-----	-----	-----
total dissolved	90, 91, 95, 102, 105	-----	-----	-----	-----	-----
Insects	-----	-----	-----	xvii, xxv, 102, 140, 160, 169, 182, 192, 200, 201, 210, 212	84	-----
plant vulnerability to	-----	-----	-----	-----	76, 156, 159	-----
Insolation: annual cycle	-----	90, 95-96, 100, 103, 108	-----	-----	-----	-----
annual mean	-----	90, 104	-----	-----	-----	-----
latitudinal variation in surface	-----	314	-----	-----	-----	-----
Institute for Energy Analysis	220, 223, 228, 236, 238, 241, 258, 260, 278, 292	-----	-----	-----	-----	-----
Instrument relocations	-----	-----	33-34, 181	-----	-----	-----
Instrumental data	-----	-----	6	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Instrumental stability	-----	-----	-----	-----	-----	13
Integrated pest management	-----	-----	-----	192	83-84	-----
Interannual climate variability	-----	167	-----	-----	-----	-----
Intercellular spaces	-----	-----	-----	17	-----	-----
Interception storage of precipitation	-----	-----	-----	-----	27	-----
Intercomparison of Parameterizations in Climate Models	-----	143	-----	-----	-----	-----
Intercomparison of Radiation Codes Used in Climate Models	-----	37, 143, 278	-----	-----	-----	-----
Interfuel substitution	xx, 224, 240, 243, 292	-----	-----	-----	-----	-----
Interglacial-glacial transitions	-----	-----	6	-----	-----	-----
Interhemispheric transfer	165	-----	-----	-----	-----	-----
Internal forcing factors	-----	-----	5	-----	-----	-----
Internal response mechanisms	-----	177	-----	-----	-----	-----
International Association of Hydrological Sciences	-----	-----	-----	-----	-----	216
International Atomic Energy Agency	17	-----	-----	-----	-----	-----
International Biological Programme	-----	-----	-----	3	-----	-----
International Carbon Unit	95	-----	-----	-----	-----	-----
International Commission on Glaciers	-----	-----	-----	-----	-----	216
International Commission on Snow and Ice	-----	-----	-----	-----	-----	216
International Council of Scientific Unions	17	-----	-----	-----	-----	216
International Energy Agency	17	-----	-----	-----	-----	-----
International Geophysical Year	34, 37	-----	69	-----	-----	110
International Glaciological Expedition to Greenland	-----	-----	-----	-----	-----	25, 26
International Hydrological Decade	-----	-----	111, 133	-----	-----	207, 217
International Institute for Applied Systems Analysis	17, 218-220, 229, 236, 239, 242, 260	-----	-----	-----	-----	-----
International Latitude Service	-----	-----	-----	-----	-----	34, 93
International Maize and Wheat Improvement Center	-----	-----	-----	-----	72	-----
International North Pacific Fisheries Commission	-----	-----	-----	-----	129	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
International relations: effects of food supply on	-----	-----	-----	-----	71	-----
International Satellite Cloud Climatology Project	-----	50, 263, 275-276	-----	-----	-----	-----
International Society for Photogrammetry and Remote Sensing	-----	-----	-----	-----	-----	235
Interspecies competition in forests	-----	-----	-----	-----	147	-----
Intertropical convergence zone	41, 51, 52, 165	-----	-----	-----	-----	-----
Intrusions from the sea	-----	-----	-----	-----	36, 83	-----
Inundation of coastal cities	-----	-----	-----	35	-----	-----
Ionization reactions	85	-----	-----	-----	-----	-----
Irminger Sea	-----	-----	-----	-----	-----	133-134
Irradiance (see Light)	-----	-----	-----	-----	-----	-----
Irrigation	122	-----	34, 116	xxi, 23, 193, 200	xvii, 82-83, 216	-----
projections of subsurface	-----	-----	-----	-----	82	-----
trickle	-----	-----	-----	-----	83	-----
wastewater-spray	-----	-----	-----	-----	83	-----
-----	-----	-----	-----	-----	190	-----
Irrigation management	-----	-----	-----	-----	45, 59, 82	-----
Irrigation need: simulation of	-----	-----	-----	-----	219	-----
Irrigation projects	-----	-----	-----	-----	-----	220
Irrigation systems: efficiencies of	-----	-----	-----	-----	34, 83	-----
Irrigation water demands for reuse of	-----	-----	-----	-----	25	-----
-----	-----	-----	-----	-----	57	-----
-----	-----	-----	-----	-----	45	-----
Isochemical conditions	103	-----	-----	-----	-----	-----
Isohydropleths: Antarctic	-----	-----	-----	-----	-----	200
Isopycnal surfaces	83, 105, 156	-----	-----	-----	-----	-----
Isopycnals	-----	179, 180, 181, 185-	-----	-----	-----	-----
Isostatic adjustment (glacial) correction of sea-level data for	-----	-----	-----	-----	-----	101, 297
-----	-----	-----	-----	-----	-----	14
Isostatic-adjustment constraints	-----	-----	-----	-----	-----	92-102
Isostatic-adjustment effects	-----	-----	-----	-----	-----	93, 94-97
Isostatic rebound	-----	-----	-----	-----	-----	12, 14, 59, 86, 188
Isostatic uplift	-----	-----	-----	-----	-----	12, 14, 59, 86, 188
Isotherms in the oceans	-----	-----	-----	-----	-----	110
Isotopes: stable and radioactive	-----	-----	-----	7	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Isotopic changes in sediments	31, 33	-----	-----	-----	-----	-----
Isotopic ratios	33, 203	-----	-----	-----	-----	-----
Isotopic time series	28, 35	-----	-----	-----	-----	-----
Israel	-----	-----	-----	-----	46	-----
Issues:						
policy	21, 217, 227-230, 243, 281	-----	-----	-----	-----	-----
scientific	9-11	-----	-----	-----	-----	-----
Itchgrass	-----	-----	-----	157, 158, 159	-----	-----

J

Jack pine	-----	-----	-----	-----	148	-----
Jacobsen-Ekblad Glacier	-----	-----	-----	-----	-----	191, 192
Jakobshavn Glacier	-----	-----	-----	-----	-----	315
Japan	-----	-----	42, 159, 160	-----	43, 97	-----
sea levels at coast of	-----	-----	-----	-----	-----	76, 78-83
Japan Sea	-----	-----	-----	-----	125	-----
Japan Trench	-----	-----	-----	-----	-----	78
JASON Society	217, 221, 260	-----	-----	-----	-----	-----
Jellyfish	-----	-----	-----	-----	107	-----
Jet stream	-----	-----	-----	-----	74	-----
Jimson weed	-----	-----	-----	160	-----	-----
Jojoba	-----	-----	-----	-----	85	-----

K

Kale	-----	-----	-----	67	-----	-----
Kamchatka Peninsula	-----	-----	-----	-----	125	-----
Kara Sea	-----	-----	127	-----	-----	-----
Kenai Current	-----	-----	-----	-----	114, 116	-----
Kenai Mountains	-----	-----	-----	-----	-----	141
Kesselwand Glacier	-----	-----	-----	-----	-----	35, 223
KIAMBRAM	-----	-----	-----	45	-----	-----
Kinematic wave theory	-----	-----	-----	-----	-----	224
Kinetic energy of oceans	-----	178	-----	-----	-----	-----
Kinetic rate coefficients	-----	223	-----	-----	-----	-----
King Glacier	-----	-----	-----	-----	-----	192

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Kitt Peak National Observatory	30, 40, 56	-----	-----	-----	-----	-----
Kittiwakes	-----	-----	-----	-----	107, 123	-----
Korff Ice Rise	-----	-----	-----	-----	-----	31, 302, 305, 306
Krakatoa	-----	199	42	-----	-----	-----
Krill	-----	-----	-----	-----	99	-----
Krypton-85	91, 156	-----	-----	-----	-----	-----
Kurile Islands	-----	-----	-----	-----	125	-----
Kuroshio meanders	-----	-----	-----	-----	-----	80
Kuskokwim River	-----	-----	-----	-----	114	-----

L

Labile reservoirs of carbon	32	-----	-----	-----	-----	-----
Labor-energy tradeoff	226	-----	-----	-----	-----	-----
Labor productivity	224, 243, 292	-----	-----	-----	-----	-----
Laboratory of Glaciology and Environmental Geophysics	28	-----	-----	-----	-----	-----
Laboratory of Tree Ring Research, University of Arizona	180	-----	-----	-----	-----	-----
Laboratory studies:						
fish	-----	-----	-----	-----	133, 137	-----
Labrador	-----	248	-----	-----	-----	-----
Labrador Current	-----	-----	121	-----	-----	-----
Labrador Sea	-----	-----	-----	-----	-----	131, 133-134, 135
Lag time:						
glacial	-----	-----	-----	-----	-----	224, 227, 243
Lag times:						
ocean-induced	297	xxi, 164, 172, 242	xxi, 77, 79	-----	-----	-----
LAGEOS satellite	-----	-----	-----	-----	-----	34, 94, 101
Lakagigar, Iceland	-----	-----	44	-----	-----	-----
Lake Kallavesi, Finland	-----	-----	130	-----	-----	-----
Lake-level data	-----	247, 269	-----	-----	-----	-----
Lake-level estimates for 6000 B.P.	-----	249	-----	-----	-----	-----
Lake levels	-----	-----	160	-----	-----	-----
Lake Mead	-----	-----	-----	-----	39	-----
Lake Superior	-----	-----	-----	-----	27	-----
Lake Suwa, Japan	-----	-----	130	-----	-----	-----
Lakes	179, 198	-----	-----	-----	-----	-----
freezeup and breakup of ice records for	-----	-----	130, 137, 139, 173	-----	-----	-----
ice records for	-----	-----	130	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Lamont-Doherty Geophysical Observatory	92	-----	-----	-----	-----	-----
Land:						
cultivated:						
area of	128					
degradation of	127, 133, 294	-----	-----	-----	-----	-----
ice extent over	-----	-----	111, 133	-----	-----	-----
snow cover over	-----	-----	114	-----	-----	-----
vertical movement of	-----	-----	-----	-----	-----	81, 84, 85, 89
Land-atmosphere exchanges	xix, 115-134, 145, 158-164, 187, 188, 194, 251, 253	-----	-----	-----	-----	-----
Land building	198	-----	-----	-----	-----	-----
Land clearing	-----	-----	-----	173	41, 43, 154, 156, 165	-----
Land cover	144, 170, 262, 263	-----	-----	-----	-----	-----
Land ice	-----	-----	-----	-----	-----	40-45, 46-58, 62-64, 242
contributions to sea level of	-----	-----	-----	-----	-----	61
discharge of	-----	-----	-----	-----	-----	58
growth and thinning of	-----	-----	-----	-----	-----	246
interactions of with ocean	-----	-----	-----	-----	-----	116-125
mass balance response of	-----	-----	-----	-----	-----	246
to climate change	-----	-----	-----	-----	-----	-----
melting of	-----	-----	-----	-----	-----	ix, 1, 7, 59
monitoring of	-----	-----	-----	-----	-----	34-36, 216-228
outflow from	-----	-----	-----	-----	-----	48
volume of continental	-----	-----	-----	-----	-----	92
Land management	-----	-----	-----	-----	79-81, 87, 89	-----
Land subsidence	-----	-----	-----	-----	36	-----
Land surface:						
role in climate system of	-----	5, 7, 62, 267	-----	-----	-----	-----
Land toxification	11	-----	-----	-----	-----	-----
Land use	9, 11, 133	-----	169	173	xvi, xvii, xviii, 150, 152, 157, 219	-----
agricultural	128	-----	-----	-----	-----	-----
Land-use change	xv, xxiii, 18, 19, 121-122, 126, 129-134, 144-145, 147, 159, 161, 168, 170, 177, 202, 204, 249, 262, 266-267, 268, 293	xxii, 195, 217, -----	-----	-----	-----	-----
Land-use data	127, 170, 294	-----	-----	-----	-----	-----
LANDSAT	125, 133	-----	-----	-----	-----	233
LANDSAT images	-----	-----	-----	-----	-----	149, 206, 225, 234-236
Langley spectrum	56	-----	-----	-----	-----	-----
Lapse rate:						
moist adiabatic	-----	88, 91	-----	-----	-----	-----

Lapse rate feedback

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Lapse rate feedback	-----	88, 89, 138, 296, 300, 301, 313, 317	-----	-----	-----	-----
Laptev Sea	-----	-----	127	-----	-----	-----
Large-scale circulation	-----	-----	-----	-----	-----	21
Larsen Ice Shelf	-----	-----	-----	-----	-----	197, 199
Larvae:						
fish (see also Fish eggs and larvae)	-----	-----	-----	-----	109	-----
first feeding of mortality of osmotic stress on soy bean looper	-----	-----	-----	-----	110	-----
-----	-----	-----	-----	-----	101, 111, 123, 128	-----
-----	-----	-----	-----	-----	120	-----
-----	-----	-----	-----	140, 169, 192	-----	-----
Last Glaciation	-----	-----	135	-----	-----	-----
Last Interglacial	-----	-----	135	-----	-----	-----
Latent heat release of	-----	93, 331, 332 27, 51, 68	-----	-----	-----	-----
Latitude	-----	-----	-----	82	-----	-----
Latitude gradients	38, 50	-----	-----	-----	-----	-----
Laurentide Ice Sheet	-----	246, 249	115	-----	-----	2, 15, 59, 93, 99
Laurie Island	-----	-----	127	-----	-----	-----
Lawrence Livermore National Laboratory	-----	217	-----	-----	-----	-----
Le Chatelier's Principle	205	-----	-----	-----	-----	-----
Leaching of salts into groundwater	-----	-----	-----	-----	45	-----
Leaf area	-----	-----	-----	ix, xxv, 37, 63, 68, 70, 74, 75, 83, 85, 89, 119, 123, 125, 128, 129, 130, 139, 148, 157, 158, 159, 187, 193, 194, 197, 198, 201, 207, 211, 212	-----	-----
irradiance per unit	-----	-----	-----	65	-----	-----
Leaf area duration	-----	-----	-----	128, 158, 159	-----	-----
Leaf area index	-----	-----	-----	43, 62, 78, 112, 130, 139	-----	-----
Leaf-level responses	-----	-----	-----	57	-----	-----
Leaf metabolism	-----	-----	-----	58	-----	-----
Leaf production	-----	-----	-----	129	-----	-----
Leaf River	-----	-----	-----	-----	35	-----
Leaf structure	-----	-----	-----	68, 69, 188	-----	-----
Leaf tissue	-----	-----	-----	13	-----	-----
Leaf water potential	-----	-----	-----	43, 74, 80, 82, 83, 112, 177, 194, 207	-----	-----
Leaves:						
carbohydrate levels of	-----	-----	-----	68	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Leaves (continued)						
dry weight of	-----	-----	-----	58, 67, 83, 157, 160	-----	-----
nitrogen content of	-----	-----	-----	43, 69	-----	-----
physiological properties of	-----	-----	-----	28, 64, 177	-----	-----
Ledum palustre	-----	-----	-----	123	-----	-----
Legal definitions of water access and ownership	-----	-----	-----	-----	37	-----
Legumes (see also specific species)	-----	-----	-----	69, 90, 191	-----	-----
Lennox-King Glacier	-----	-----	-----	-----	-----	192
Lettuce breeding	-----	-----	-----	189	-----	-----
Leukemia	-----	-----	-----	-----	178	-----
Lice	-----	-----	-----	140	-----	-----
Lichens	-----	-----	-----	147	-----	-----
Life-cycle stages of fish	-----	-----	-----	-----	105, 109, 118, 125, 129, 134, 135	-----
Life-cycle timing	-----	-----	-----	xxiii, 70, 89, 167, 168	-----	-----
Life prolongation:						
human	-----	-----	-----	-----	184	-----
Light	-----	-----	-----	xxi, 5, 6, 13, 57, 60, 83, 157, 178	-----	-----
angle of incidence of	-----	-----	-----	65	-----	-----
effects on photosynthesis of	-----	-----	-----	65, 72, 76, 114	-----	-----
Light absorption	-----	-----	-----	-----	129	-----
Light compensation point	-----	-----	-----	73, 188, 208	-----	-----
Light energy capture	-----	-----	-----	39	-----	-----
Light extinction values	-----	182	-----	-----	-----	-----
Light intensity	-----	-----	-----	xviii, xxv, 21, 27, 60, 120, 165, 178, 188, 201, 208	-----	-----
Light penetration	-----	-----	-----	130	-----	-----
Light saturation	-----	-----	-----	57, 65	-----	-----
Light utilization efficiency	-----	-----	-----	64-65, 121, 143, 144, 176	-----	-----
Lignin	-----	-----	-----	134	-----	-----
Limber pine	-----	-----	-----	180	-----	-----
Limestone	5	-----	-----	-----	-----	-----
Limiting factors of plant growth	-----	-----	-----	5	-----	-----
Line-by-line technique	-----	33	-----	-----	-----	-----
Literature surveys	-----	-----	-----	-----	137	-----
Lithosphere	188, 195, 204, 299	62	-----	-----	-----	-----
definition	-----	60	-----	-----	-----	94
thickness of	-----	-----	-----	-----	-----	-----

Lithospheric plates

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Lithospheric plates	-----	163	-----	-----	-----	-----
Litter	115, 119, 125, 143, 159, 164, 187, 263	-----	-----	-----	-----	-----
decomposition of production of quality of	-----	-----	-----	134, 210	-----	-----
-----	-----	-----	-----	24, 135	-----	-----
-----	-----	-----	-----	119	-----	-----
Litterfall	-----	-----	-----	135	-----	-----
Little Ice Age	257	17, 166	6	-----	-----	-----
Livestock breeds: purity of	-----	-----	-----	-----	76	-----
Livestock production	-----	-----	-----	-----	72	-----
Loblolly pine	-----	-----	-----	69, 127, 157, 160, 179, 195	-----	-----
Locoweed	-----	-----	-----	160	-----	-----
Lodging	-----	-----	-----	77	-----	-----
Loess	181	-----	-----	-----	-----	-----
Logging	17	-----	-----	-----	-----	-----
Longwave radiation:	-----	-----	-----	-----	-----	-----
absorption and emission of by carbon dioxide	-----	vii, 27, 29, 30, 40, 270	17, 165, 167	-----	-----	-----
cooling rates for downward	-----	31, 37	-----	-----	-----	-----
effect on radiation budget of	-----	30, 39, 40, 43, 138, 310, 311	-----	-----	-----	-----
emission from the stratosphere of flux density of fluxes of outgoing	-----	40, 43	-----	-----	-----	-----
parameterization of spectral distribution of flux of upward	-----	33-39, 68	-----	-----	-----	-----
variations in downward flux of	-----	-----	15, 27, 167	-----	-----	-----
Longwave radiation balance of the Earth	-----	xvii, 7, 19, 30, 31, 193	-----	-----	-----	-----
Longwave radiation emission	-----	40, 43, 291	-----	-----	-----	-----
Longwave radiation fluxes	-----	38, 65	-----	-----	-----	-----
change in downward	-----	35	-----	-----	-----	-----
-----	-----	xxiv, 6, 35, 43, 93, 206, 264, 285, 325, 326, 329	-----	-----	-----	-----
increase in upward	-----	43	-----	-----	-----	-----
-----	-----	7, 27, 30, 43, 87, 88, 153, 270, 289, 292, 315, 316, 325, 329, 331	-----	-----	-----	-----
Longwave radiation forcing from increased carbon dioxide	-----	43	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Longwave radiative budget	-----	30, 39, 40	-----	-----	-----	-----
Los Angeles	-----	203	-----	-----	-----	-----
Lower Grindelwald Glacier	-----	-----	-----	-----	-----	224
Lucerne	-----	-----	-----	61, 75, 103, 105-109, 216-217	-----	-----
Lumber industry	-----	-----	-----	-----	19, 149	-----
Lunar forcing	-----	-----	169	-----	-----	-----
Lunar tidal cycle	191	-----	-----	-----	-----	-----

M

Mackenzie Delta	-----	-----	131	-----	-----	-----
Mackenzie Valley	-----	-----	132	-----	-----	-----
Macronutrients	-----	-----	-----	113	-----	-----
Macrophytes	97	-----	-----	-----	-----	-----
Madeira	-----	204	-----	-----	-----	-----
Magmatism	195	-----	-----	-----	-----	-----
Magnesian calcites: dissolution of	97	-----	-----	-----	-----	-----
Main stem heights	-----	-----	-----	83	-----	-----
Maize	-----	-----	-----	xxi, 6, 23, 25, 57, 59, 61, 63, 68, 70, 71, 75, 77, 78, 103, 105-109, 111, 112, 114, 123, 126, 157, 158, 159, 179, 189, 192, 200, 222-229	-----	-----
Malaria	-----	-----	-----	-----	183, 194	-----
Malkmus model	-----	-----	15	-----	-----	-----
Malnutrition	-----	-----	-----	-----	42, 71, 195, 200	-----
Management practices: agricultural forestry	-----	-----	-----	xxv, 46, 187 187	-----	-----
Manitoba	-----	248	132	-----	-----	-----
Mannheim Ephemerides	-----	-----	31	-----	-----	-----
Mantle density	-----	-----	-----	-----	-----	99
Mantle viscosity	-----	-----	-----	-----	-----	100, 101
Mantle viscosity profile	-----	-----	-----	-----	-----	34
Mapping of ice surfaces: topographic	-----	-----	-----	-----	-----	67, 235
Mapping techniques	-----	-----	160	-----	-----	-----

Maps

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Maps	18, 133, 134, 166, 170-171, 180, 265	-----	39	-----	-----	-----
Antarctic	-----	-----	-----	-----	-----	29, 30, 174, 175, 200, 282-286, 302, 318
Arctic	-----	-----	-----	-----	-----	146
Atlantic Ocean balance-velocity-distribution	-----	-----	-----	-----	-----	132, 136, 137
Brunt Ice Shelf digitized	-----	-----	117	-----	-----	174, 175
Europe flowline	-----	-----	-----	-----	-----	202
glacier topographic	-----	-----	-----	-----	-----	85, 87-89
global isotherm for 18,000 B.P.	-----	247	-----	-----	-----	183
global vegetation	-----	-----	-----	-----	153, 160	235
Greenland ice-condition	-----	-----	123	-----	-----	26, 157, 158, 163
ice-thickness	-----	-----	-----	-----	-----	173, 174, 180, 181
isochrome	-----	251	-----	-----	-----	-----
isotherm	-----	250	-----	-----	-----	-----
Japan	-----	-----	-----	-----	-----	81-83
McMurdo Sound	-----	-----	-----	-----	-----	227
North America	-----	-----	-----	-----	-----	95
North Pacific and Bering Strait	-----	-----	-----	-----	112	-----
paleoclimatic	-----	251	-----	-----	-----	-----
permafrost	-----	-----	131	-----	-----	-----
Ronne-Filchner Ice Shelf	-----	-----	-----	-----	-----	32, 205
Ross Ice Shelf	-----	-----	-----	-----	-----	30, 123, 179-182, 184, 189
seasonal climate variable	-----	-----	-----	-----	160	-----
soil	117	-----	-----	-----	-----	-----
vegetation-type	-----	-----	-----	200	-----	-----
Wordie Ice Shelf	-----	-----	-----	-----	-----	201
world	-----	-----	-----	-----	-----	22, 130, 140, 142
MAPSAT	-----	-----	-----	-----	-----	235
Marginal Ice Zone Experiment	-----	-----	126	-----	-----	-----
Marine air temperatures nighttime	-----	-----	57, 98, 170	-----	-----	-----
-----	-----	-----	61-65, 75-76	-----	-----	-----
Marine biosphere	50	-----	-----	-----	-----	-----
Marine biota	291	-----	-----	-----	-----	-----
Marine embayments: artificial fertilization of	-----	-----	-----	-----	99	-----
Marine fisheries	-----	-----	-----	-----	97-140	-----
Marine instability	-----	-----	-----	-----	-----	279, 280-284
Marine organisms	169, 180	-----	-----	-----	-----	-----
Marine photosynthesis	88	-----	-----	-----	-----	-----
Marine plankton data	-----	247, 269	-----	-----	-----	-----
Marine primary productivity	-----	-----	-----	-----	97, 101, 105, 116, 118, 137, 139, 140	-----
Marine productivity	49, 57	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Marine sediments	5, 32	-----	-----	-----	-----	-----
Marine transgressions	198	-----	-----	-----	-----	-----
Market penetration	240, 292	-----	-----	-----	-----	-----
Markets: agricultural	-----	-----	-----	-----	72	-----
Mass balance (see also Glaciers, mass balance of):						
Antarctic	-----	-----	-----	-----	-----	33
uncertainties in	-----	-----	-----	-----	-----	28
fluctuations of	-----	-----	-----	-----	-----	24
time series of	-----	-----	-----	-----	-----	36
volume fluxes of	-----	-----	-----	-----	-----	44
Mass-balance analyses	-----	-----	-----	-----	-----	42, 44, 183, 258, 319
Mass-balance equations	85	-----	-----	-----	-----	155-162, 164-167, 233
Mass-balance terms: changes of with climate	-----	-----	-----	-----	-----	25, 251, 262, 263
changes of with elevation	-----	-----	-----	-----	-----	251
of equilibrium line	-----	-----	-----	-----	-----	-----
Mass extinctions	205, 300	-----	-----	-----	-----	-----
Mass load of the planet (see also Ice and water load)	-----	-----	-----	-----	-----	97, 98, 99, 102
Mass spectrometry	29	-----	-----	-----	-----	-----
Mauna Loa	xvii, 5, 6, 18, 19, 30, 34, 36-43, 47, 48, 49, 53, 55, 70, 143, 153, 158-159, 163, 168, 250, 252, 254, 255, 256, 268, 269, 271, 275, 276	vi, 83, 1	vi	vi, xi, xxiv, 177, 179, 180	11	-----
Maunder minimum	-----	166	46	-----	-----	-----
McDonald Ice Rumples	-----	-----	-----	-----	-----	200
McMurdo Sound	-----	-----	-----	-----	-----	117, 118, 277, 278
Measurement networks	xxii, 57, 280	-----	-----	-----	-----	-----
MEDECS	-----	-----	-----	148	-----	-----
Medical research needed	-----	-----	-----	-----	197	-----
Medieval Warm Epoch	-----	17, 241, 269	-----	-----	-----	-----
Mediterranean Ecosystem Simulator	-----	-----	-----	148	-----	-----
Meetings on biological aspects of global carbon dioxide enrichment	-----	-----	-----	4	-----	-----
Meighen Ice Cap	-----	-----	-----	-----	-----	24, 145, 147, 148, 149
Melanoma and solar radiation	-----	-----	-----	-----	183	-----

Melt rates

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Melt rates (glacial)	-----	-----	-----	-----	-----	21, 28, 44, 121, 122, 124, 150, 202, 308, 309-310
Melt rates: patterns of	-----	-----	-----	-----	-----	204
Melt series data	-----	-----	-----	-----	-----	152
Meltwater carbon-dioxide-induced production of glacial plumes of	29	-----	102, 104	-----	102	34, 291 25, 42, 43, 251
Meridional fluxes	45	-----	-----	-----	-----	-----
Meridional surface exchanges	45	-----	-----	-----	-----	-----
Meridional transports of heat and moisture	-----	97, 161	-----	-----	-----	-----
Meridional winds	-----	9	-----	-----	-----	-----
Meristem production	-----	-----	-----	132	-----	-----
Mesic environments	-----	-----	-----	127	-----	-----
Mesocosm experiments on fish	-----	-----	-----	-----	134, 135	-----
Mesophyll cells	-----	-----	-----	69, 83, 85, 113	-----	-----
Mesophyll resistance to carbon dioxide	-----	-----	-----	141	-----	-----
Mesoscale eddies	-----	-----	-----	-----	-----	104
Metabolic changes	134	-----	-----	-----	-----	-----
Metabolic losses of fish	-----	-----	-----	-----	108	-----
Metabolic rates in fish	-----	-----	-----	-----	105	-----
Metabolism: terrestrial	131, 133, 205	-----	-----	-----	-----	-----
Metamorphism	193	-----	-----	-----	-----	-----
Meteorological events	-----	-----	-----	38	-----	-----
Meteorological records	-----	-----	-----	-----	-----	207
Meteorologists: role of in city planning	-----	-----	-----	-----	201	-----
Methane	xix, 36, 54, 91, 135, 188, 198, 202, 203, 204, 205, 242, 282, 293, 297, 298, 300	5, 113, 193, 194-195, 210, 219, 223, 264	23, 24, 167, 183	-----	-----	-----
preindustrial concentrations of radiative effects of increases in	-----	194	-----	-----	-----	-----
Methyl chloride	293	-----	-----	-----	-----	-----
Mexico	-----	132	-----	-----	-----	-----
Michaelis-Menten kinetics	-----	-----	-----	xxiv, 174	-----	-----
Microbial biomass	-----	-----	-----	135	-----	-----
Microbial growth in soil	-----	-----	-----	132	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Microclimate changes	-----	-----	-----	66	-----	-----
Microcosm studies	-----	-----	-----	-----	137	-----
Microenvironments	-----	-----	-----	23, 27	-----	-----
Microorganisms	199	-----	-----	-----	-----	-----
Mid-ocean gyres	-----	-----	-----	-----	-----	60
Migration routes: displacement of fish	-----	-----	-----	-----	98	-----
Migration timing of fish	-----	-----	-----	-----	124	-----
Milankovitch hypothesis: definition	-----	16	-----	-----	-----	-----
Milankovitch radiation variations	-----	-----	4, 115	-----	-----	-----
Millet	-----	-----	-----	75, 131, 158, 192	75	-----
Mineral carbonates	203	-----	-----	-----	-----	-----
Mineral weathering	-----	-----	-----	-----	45	-----
Mineralization rates	-----	-----	-----	132, 135, 139, 147, 148, 208, 212	-----	-----
Missing carbon problem	5, 9, 252	-----	-----	-----	-----	-----
Missing sinks	253, 256, 258, 268, 271	-----	-----	-----	-----	-----
Mississippi River Delta	-----	-----	-----	-----	-----	74
Mississippi State University	-----	-----	-----	13	-----	-----
MIT Energy Laboratory	241	-----	-----	-----	-----	-----
MIT Projection Exercise	278	-----	-----	-----	-----	-----
Mitigating strategies	12, 266, 278, 280, 282	169	-----	-----	-----	-----
Mitochondria	-----	-----	-----	134	-----	-----
Mixing (oceanic): rate of vertical	93, 169 150	-----	-----	-----	-----	-----
Mixing times (oceanic)	94	-----	-----	-----	-----	-----
Model classification	-----	-----	-----	38, 39	-----	-----
Model complexity	-----	-----	-----	35, 45-46	-----	-----
Model development	xxiii, 106, 168-171, 293-295	185, 277, 361	-----	35-48, 76-83, 90, 101, 102, 140-143, 210, 211, 213	-----	-----
Model evaluation	-----	-----	-----	37, 42-45	-----	-----
Model spatial resolution	168	-----	-----	-----	-----	-----
Modeling	3, 17, 32, 249	-----	xvii, 11, 184-185	xix, 46, 140-144, 210	-----	-----
advantages and disadvantages of climate computer costs of error in	-----	-----	9	-----	-----	-----
	-----	-----	-----	14	-----	-----
	-----	-----	-----	14	-----	-----
	-----	-----	-----	41, 42	-----	-----
	-----	-----	-----	xx	-----	-----

Modeling

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Modeling (continued)						
forest succession	-----	-----	-----	-----	19	-----
hydrologic	-----	-----	-----	-----	56	-----
causal approach	-----	-----	-----	-----	56	-----
empirical approach	-----	-----	-----	-----	56	-----
inadequacies of	xx, 10, 22, 152, 155, 164, 170-171, 238-239, 257, 275, 281, 291	-----	-----	-----	-----	-----
model-to-model variability in	-----	83-144	-----	-----	15	-----
problems of	-----	77-78	-----	-----	-----	-----
recommendations for	-----	-----	-----	ix, xix, xx, 84, 213	-----	-----
spatial resolution of	-----	-----	-----	-----	14, 17	-----
time intervals of	-----	-----	-----	-----	14, 17	-----
uncertainties in	-----	-----	xxii	-----	-----	42
Models:						
ablation	-----	-----	-----	-----	-----	159
advective	155	-----	-----	-----	-----	-----
advective-diffusive	271	-----	-----	-----	-----	-----
agricultural	-----	-----	-----	xx	-----	-----
approaches of	-----	ix, 36	-----	-----	-----	-----
atmosphere-ocean climate	-----	-----	137, 184	-----	-----	-----
atmosphere-ocean system	147-158	-----	-----	-----	-----	-----
atmospheric	168-169	-----	70, 72	-----	-----	-----
atmospheric chemistry	135	-----	-----	-----	-----	-----
atmospheric circulation	134, 165-168, 298	-----	-----	-----	-----	-----
atmospheric pollutant	-----	-----	-----	-----	159	-----
atmospheric tracer	49	-----	-----	-----	-----	-----
autoregressive moving average	-----	-----	-----	-----	47	-----
baroclinic-eddy	-----	-----	-----	-----	-----	47
behavioral	227-228, 281	-----	-----	-----	-----	-----
biogeochemical	195	-----	-----	-----	-----	-----
biological process	95	-----	-----	-----	-----	-----
biomass change	-----	-----	-----	-----	163	-----
bookkeeping	-----	-----	-----	182	-----	-----
box	104, 228	-----	-----	-----	-----	-----
box-advection-diffusion	100	-----	-----	-----	-----	-----
box-diffusion	98-100, 106, 146, 147-148, 150-153	-----	-----	-----	-----	-----
Bryson-Dittberner	-----	168	-----	-----	-----	-----
carbon cycle	104, 143-171, 204, 249, 269, 270-272, 274, 280	-----	-----	-----	-----	-----
characteristics of	-----	83-144	-----	-----	-----	-----
circulation	-----	-----	-----	-----	-----	125
climate	32	xvii, 5, 36, 261, 283, 323, 339	9, 79, 113	-----	14, 60, 134, 139, 153, 159, 162, 189	3, 47, 65, 268
cloud	-----	307	-----	-----	-----	-----
Community Climate	-----	-----	114	-----	-----	-----
comparison of with	-----	38-39, 182, 334	-----	-----	-----	-----
observed climatic	-----	-----	-----	-----	-----	-----
variations	-----	-----	-----	-----	-----	-----
competition and population	-----	-----	-----	141	-----	-----
computer	-----	-----	-----	35	-----	-----
conceptual	-----	-----	-----	36	-----	-----
constant airborne fraction	273, 279	-----	-----	-----	-----	-----
correlative	-----	-----	-----	39	-----	-----
coupled atmosphere-ocean	-----	77, 153, 185, 207, 267, 277, 279	-----	-----	-----	267-274

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Models (continued)						
coupled ice-ocean-atmosphere			137			
crop-climate				66, 77-78, 201		
crop-pest system					84	
crop protein					219	
crop-species				7, 43, 79, 88		
crop yield					57	
cropping-system				xx, 47, 84, 210		
cryospheric		72, 266				
cumulus		302				
definition		13, 65, 261		35		
deterministic					137, 139	
dynamic				37		28
dynamic/thermodynamic ice						125
Earth						15, 34, 61
econometric					xvii, 88	
economic	278, 280					
ecosystem					35	
empirical				37, 39, 40, 46, 78-79	152	
energy balance (see also Energy balance models)		13, 84-85, 141, 153, 161, 173, 265, 267, 283-289, 290, 340, 350, 354, 359	xxi, 43, 77, 79, 113			3, 270
energy-economic	18, 22, 77, 78					
equilibrium sensitivity		20, 243				
ERGB	224-226					
finite-difference						279
finite-element (see also Finite-element analysis of ice shelves)						287, 292-297
fish population dynamics					130	
fishery					130, 134	
fixed-depth mixed-layer		100				
ocean						
flowline-reconstruction						52, 279, 280
forest disease					159	
forest simulation					152, 158-160, 162	
forest successional				45, 141		
forest temperature-change					152	
response						
general circulation	3, 57, 135, 166, 168, 169	xx-xxii, 13, 36, 50, 70-71, 73-75,	7, 8, 9, 67, 77, 112, 114, 129		14, 60, 139, 153, 162	
		76, 89-138, 141-144, 162, 184, 215, 242, 253, 264, 265				
geochemical	31, 34, 145					
geologic	56					
GFDL		73, 74, 90, 92, 98, 100, 101, 119-120, 121, 128, 144, 156, 326, 348	114, 128			
GISS		98, 114-116, 121, 127, 137-138, 216, 345, 349	114, 129			261, 301, 309
glacial flow line						258
glacio-isostatic						65, 68

Models

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Models (continued)						
global carbon	-----	-----	-----	179, 182	-----	-----
global energy balance	-----	153, 265	-----	-----	-----	-----
grid-point	104	-----	-----	-----	-----	-----
heat balance	-----	70	-----	-----	-----	-----
hierarchy of hydrodynamic	-----	19, 261, 266, 340	-----	-----	-----	-----
hydrodynamic	84	-----	-----	-----	-----	-----
hydrologic	-----	-----	-----	197, 198, 201	-----	-----
hydrometeorological	-----	-----	-----	-----	60	42
ice sheet	-----	-----	115, 129, 134	-----	-----	-----
ice-sheet-dynamics	-----	-----	-----	-----	-----	251, 301-315
ice-shelf	-----	-----	-----	-----	-----	207, 279-300
ice-stream	-----	-----	-----	-----	-----	279-300, 306-309, 317-328
IIASA	226	-----	-----	-----	-----	-----
improvements needed in insect population	-----	275	-----	-----	-----	41, 65
intercomparison of	-----	-----	xxiv, 83-144, 206, 278, 305, 307, 339-340, 341, 345-348, 350, 361	-----	159	-----
isopycnal mixing	156-157	-----	-----	-----	-----	-----
isopycnal ventilation	156	-----	-----	-----	-----	-----
land surface	-----	72-73, 266	-----	-----	-----	-----
layered	154	-----	-----	-----	-----	-----
leaf photosynthesis	-----	-----	-----	39, 40, 42, 46, 140-141	-----	-----
limitations of	-----	141-142	-----	-----	-----	-----
line-by-line	-----	37, 50, 263	-----	-----	-----	-----
linear balance	-----	-----	-----	-----	-----	222, 252
linear programming	102, 228, 229, 240	-----	-----	-----	-----	-----
linking	300	-----	-----	-----	-----	-----
log-linear extrapolation	281	-----	-----	-----	-----	-----
longwave radiative transfer	-----	36-39	-----	-----	-----	-----
Malkmus absorptance	-----	-----	15	-----	-----	-----
Manabe-Stouffer	-----	-----	-----	-----	74	-----
marine primary productivity	-----	-----	-----	-----	139, 140	-----
mass-balance	-----	-----	-----	-----	-----	22-23, 139, 140
mathematical	xv, 21, 97-102	xx, 12-16, 59, 83, 265, 283	-----	6, 36, 157	-----	-----
mechanistic	-----	-----	-----	37, 39, 41, 79, 84, 87, 89, 210	-----	-----
microclimatic	-----	-----	133	-----	-----	-----
mixed layer ocean	-----	139, 144	114	-----	-----	-----
multibox	10, 101-102, 150-152, 156-161, 169	-----	-----	-----	-----	-----
multibox ocean	-----	-----	-----	-----	-----	270-271
multidimensional	100	-----	-----	-----	-----	-----
narrow band	-----	33-34, 37, 39, 263	-----	-----	-----	-----
native plant species	-----	-----	-----	xx, 43, 44, 45	-----	-----
NCAR	-----	92, 93, 116-118, 114, 121, 127, 206, 216, 344, 348	-----	-----	-----	-----
nested-system	204-205	-----	-----	-----	-----	-----
Nordhaus and Yohe	224-226	-----	-----	-----	-----	-----
numerical	-----	xvii, 14, 271, 275, 277, 341	xxviii, 8, 165, 184	-----	-----	53, 66, 317
definition	-----	14	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Models (continued)	-----	-----	-----	-----	vii	-----
nutrient cycling	-----	-----	-----	-----	159	-----
ocean:						
regionalized	149	-----	-----	-----	-----	-----
ocean circulation	84, 88, 91, 93, 95	-----	126	-----	134, 178	-----
ocean sea ice	-----	96, 100	-----	-----	-----	-----
ocean transport	-----	164, 182	-----	-----	-----	-----
oceanic	169-170, 291	72, 178, 266	-----	-----	-----	-----
one-dimensional	-----	157, 158, 161, 264, 269, 340	-----	-----	-----	114, 270-271
Oregon State University	-----	92, 96, 144, 292, 295, 296, 342, 354-355	-----	-----	-----	48
outcrop diffusion	100, 150	-----	-----	-----	-----	-----
performance of	-----	5, 73	-----	-----	-----	-----
physical	-----	-----	-----	36	-----	-----
physical basis of	-----	65-70	-----	-----	-----	-----
plant-growth	-----	-----	-----	ix, xxi, 7, 35, 36-37, 45, 101, 210, 211	-----	-----
plant production and	117	-----	-----	-----	-----	-----
decomposition	-----	-----	-----	-----	-----	-----
predictive	103, 106	-----	-----	-----	-----	-----
primary	143	-----	-----	-----	-----	-----
projections of	-----	217-221	-----	-----	-----	-----
radiation	-----	-----	167	-----	-----	-----
radiation transport	-----	19	-----	-----	-----	-----
radiative convective	-----	13, 49, 70, 85-89, 137, 141, 265, 266, 289-315, 331, 340, 348, 352-353	114	-----	-----	-----
radiative transfer	-----	36, 51, 85, 290	-----	-----	-----	-----
rainfall runoff	-----	-----	-----	46, 61	-----	-----
research needed on	-----	143-144, 224-225	-----	-----	-----	-----
reservoir simulation	-----	-----	-----	46, 48	-----	-----
results of	-----	-----	165	-----	-----	-----
uncertainties in	-----	xxi, 221-223, 340, 344-345, 361	-----	-----	-----	-----
sea ice	-----	-----	114, 125, 128, 129	-----	-----	-----
sensitivity of	266	-----	15, 74, 90, 283, 331, 342, 344, 349, 356	-----	-----	-----
simplified climate	-----	69-70, 83-89, 265, 348-350	-----	-----	-----	-----
soil water	-----	-----	-----	219	-----	-----
spatial resolution of	-----	13	-----	-----	-----	-----
static	-----	-----	-----	37	-----	-----
statistical dynamical	-----	-----	-----	-----	-----	-----
steady-state	-----	70	-----	-----	-----	3, 40, 62
stochastic element	-----	-----	-----	xx, 45, 47, 213	-----	-----
storm	-----	-----	-----	-----	47	-----
streamflow	-----	-----	-----	-----	46, 47	-----
supply-side	240	-----	-----	-----	-----	-----
surface equilibrium	-----	-----	132	-----	-----	-----
temperature	-----	-----	-----	-----	-----	-----
temporal and spatial	-----	278, 279	-----	-----	-----	-----
scales of	-----	-----	-----	-----	-----	-----
terrestrial ecosystem	158, 162-163, 170-171	-----	-----	-----	-----	-----
thermal-convection	-----	-----	-----	-----	94	-----

Models

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Models (continued)						
thermodynamic climate	-----	85, 290	-----	-----	-----	-----
thermodynamic-dynamic sea ice	-----	-----	126	-----	-----	-----
three-dimensional	-----	13, 70, 269, 326, 340	-----	-----	-----	40, 52
three-dimensional ocean	105, 169, 280, 295	-----	-----	-----	-----	-----
time-dependent	-----	151-186, 267, 268	-----	-----	-----	-----
time-trend	227, 237	-----	-----	-----	-----	-----
transient response	-----	-----	81	-----	-----	-----
trophic level	-----	-----	-----	-----	130	-----
two-dimensional	-----	-----	-----	24	-----	-----
two-dimensional climate	-----	40	-----	-----	-----	-----
two-dimensional ocean	155-157	-----	-----	-----	-----	-----
UKMO	-----	96	-----	-----	-----	-----
validated	-----	-----	-----	80	-----	-----
validation of	xv, xvii, 21, 152-158, 238-239, 263, 296	-----	-----	xx, xxi, 41, 82-84, 88, 90, 143, 144, 168, 169, 212, 213	60	-----
data sets for variable-aggregation verification of	-----	-----	-----	82-83	-----	-----
definition	-----	14	-----	-----	-----	-----
viscoelastic	-----	-----	-----	-----	94, 95, 99, 100	-----
water-balance	-----	-----	-----	-----	60	-----
watershed	-----	-----	-----	-----	xvi, 34-35, 59	-----
wide-band	-----	34, 35, 37, 263	-----	-----	-----	-----
zonally averaged energy balance climate	-----	161	-----	-----	-----	-----
Moist adiabatic adjustment	-----	143	-----	-----	-----	-----
Moist adiabatic lapse rate	-----	206, 297, 299, 301	-----	-----	-----	-----
Moist adiabatic lapse rate feedback	-----	88, 91, 316	-----	-----	-----	-----
Moisture (see also Water vapor):						
availability of variations of	-----	-----	169	-----	-----	-----
	134	-----	-----	-----	-----	-----
Moisture fluxes	-----	-----	-----	-----	25, 56	-----
Moisture stresses on crops	-----	-----	-----	-----	77	-----
Moisture transition zone	-----	-----	-----	-----	72	-----
Molecular diffusion	143	-----	-----	-----	-----	-----
Mollisols	-----	-----	-----	190	80	-----
Monitoring of carbon sources and sinks	17, 18-19, 56, 57, 92, 103, 132	-----	-----	-----	-----	-----
Monitoring systems:						
carbon dioxide	-----	-----	-----	xix, 14	11	-----
Monsoon Experiment	-----	38	-----	-----	-----	-----
Monsoon precipitation	-----	120, 131	121, 156	-----	-----	-----
Monsoonal circulation	-----	-----	-----	-----	-----	42, 63

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Montane regions	197	-----	-----	-----	-----	-----
Monte Carlo techniques	xxi, 23, 222, 224, 225, 226, 240, 241, 267, 273-276, 292	-----	-----	-----	-----	-----
<i>Monthly Climatic Data for the World</i>	-----	-----	69	-----	-----	-----
Montsouris Observatory	37	-----	-----	-----	-----	-----
Moraines	-----	-----	-----	-----	-----	197, 207
Morainic deposits	-----	-----	-----	-----	-----	224
Morbidity statistics	-----	-----	-----	-----	174	-----
Morphological responses	-----	-----	-----	123	-----	-----
Mortality:						
ambient temperature and barometric pressure and climate variables and fetal and infant:					178, 179	-----
seasonal variation in meteorological variables and					179	-----
nonclimatic effects on relative humidity and					178	-----
-----					178, 184	-----
-----					179-188	-----
-----					187-188, 198	-----
-----					180-181	-----
Mortality and morbidity: seasonality of	-----	-----	-----	-----	177-184	-----
Mortality from all causes	-----	-----	-----	-----	178, 184	-----
Mortality rate: regional differences in	-----	-----	-----	-----	201	-----
Mortality statistics	-----	-----	-----	-----	174, 178	-----
Mosquito breeding	-----	-----	-----	-----	183, 194, 216	-----
Mosses	-----	-----	-----	147	-----	-----
Mount St. Helens	-----	-----	43	-----	-----	-----
Mountain building	194	-----	-----	-----	-----	-----
Mulching	-----	-----	-----	-----	81, 83	-----
Multiple scattering	-----	46	-----	-----	-----	-----
Multivariate (fingerprint) strategy	-----	-----	7, 9, 10, 82, 167, 174, 175, 180, 184	-----	-----	-----
Murres	-----	-----	-----	-----	107, 123	-----
Mycorrhizal fungi	-----	-----	-----	xxv, 132, 188, 190, 201	-----	-----

N

Nankei Trough	-----	-----	-----	-----	-----	78
National Academy of Sciences	130, 239, 240-241	-----	-----	-----	-----	-----
National Bureau of Standards	17, 41	-----	-----	-----	-----	-----

National Climate Program

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
National Climate Program	-----	182	-----	-----	-----	-----
National Climatic Data Center	-----	-----	69	-----	-----	-----
National Environmental Satellite Data and Information Service	-----	-----	117	-----	-----	-----
National Marine Fisheries Service	-----	-----	-----	-----	97	-----
National Oceanic and Atmospheric Administration	19, 40	-----	41	-----	-----	-----
National Research Council global warming estimate of	242	-----	-----	-----	13	-----
-----	-----	-----	-----	-----	14	-----
National Science Foundation	242	-----	-----	-----	-----	-----
Native plant species	-----	-----	-----	ix, xxii, xxiv, 7, 101, 119	-----	-----
responses of	-----	-----	-----	13, 26, 119, 199	-----	-----
Natural climate: analysis of variability in baseline	-----	-----	181	-----	-----	-----
-----	-----	-----	4, 166, 181	-----	-----	-----
Natural climate variability	-----	-----	79, 173, 180	-----	-----	-----
Natural ecosystems	-----	-----	-----	25, 101	-----	-----
Natural gas	72, 203	-----	-----	191	-----	-----
Natural gas combustion: emissions of	66-67	-----	-----	-----	-----	-----
Natural gas liquids	75	-----	-----	-----	-----	-----
Natural selection	-----	-----	-----	xxii, xxiv, 119, 187, 199, 200, 207	-----	-----
Natural sources of carbon dioxide	-----	-----	-----	25	-----	-----
Navigation	-----	-----	-----	-----	39	-----
Navy-NOAA Joint Ice Center	-----	-----	122	-----	-----	121
Negative feedback	-----	-----	-----	138	-----	-----
Net assimilation rate	-----	-----	-----	111, 158, 159, 218, 223, 224, 231, 235, 237, 243, 249, 250, 261, 264, 265	-----	-----
Net atmospheric flux	189	-----	-----	-----	-----	-----
Net biotic flux	xx, 121, 127-129	-----	-----	-----	-----	-----
Net carbon input	-----	-----	-----	111	-----	-----
Net ecosystem carbon storage	-----	-----	-----	45, 136-137	-----	-----
Net ecosystem productivity	57	-----	-----	xxii, xxiii, 173, 174, 210	20	-----
Net photosynthesis	-----	-----	-----	40, 60, 72, 78, 120, 122, 123, 212	-----	-----
Net primary productivity	6, 57, 96-97, 118-119, 143, 146, 161, 177, 186, 201, 265	-----	-----	134, 135, 136, 162, 173, 174, 176, 181	147	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Netherlands	242	-----	-----	-----	-----	-----
Networks:						
atmospheric carbon dioxide monitoring	xxiii, 17, 18-19, 56, 57, 92, 103, 132	-----	-----	-----	-----	-----
Neva River	-----	-----	130	-----	-----	-----
New Zealand	-----	-----	-----	-----	127	143
Niche separation:						
seasonal	-----	-----	-----	162	-----	-----
Nile River	-----	-----	160	-----	41	-----
NIMBUS-6 satellite	-----	-----	-----	-----	-----	198
NIMBUS satellites	-----	28, 202	-----	-----	-----	-----
Nimrod Glacier (see also East Antarctic outlet glacier)	-----	-----	-----	-----	-----	31, 188-190, 192, 194
flowline from	-----	-----	-----	-----	-----	190, 193
Nitrification:						
bacterial	-----	197	-----	-----	-----	-----
Nitrogen	88, 90, 97, 105, 170, 300	-----	-----	6, 81, 87, 190, 209	-----	-----
Nitrogen content of leaves	-----	-----	-----	43, 69	-----	-----
Nitrogen cycle	9, 203, 293, 299	-----	-----	-----	-----	-----
Nitrogen deficiency of plants	-----	-----	-----	74, 87, 175, 176	150	-----
Nitrogen fixation	-----	-----	-----	xxv, 14, 113, 132, 135, 188, 189, 191, 209, 210, 212	-----	-----
Nitrogen fixing bacteria	-----	-----	-----	69, 135, 190	-----	-----
Nitrogen flux	204	-----	-----	-----	-----	-----
Nitrogen oxides	91, 135, 203, 242, 282, 293	-----	17, 23, 24, 167, 183	199, 212	-----	-----
sources of	-----	197, 219, 223	-----	-----	-----	-----
Nitrogen use efficiency	-----	-----	-----	191	-----	-----
Nitrous oxide	-----	113, 193, 196-197, 223, 264, 268-269	-----	-----	-----	-----
radiative effects of increases in	-----	193, 264	-----	-----	-----	-----
NOAA-GMCC sampling network	19, 40, 133, 250	-----	-----	-----	-----	-----
Nobel Symposium No. 20	-----	-----	-----	3	-----	-----
Node formation	-----	-----	-----	130	-----	-----
Nodule number	-----	-----	-----	69	-----	-----
Noise:						
climatic	-----	-----	xxi, 5, 11, 24-25, 167	-----	-----	-----
definition	-----	14	-----	-----	-----	-----
instrumental	-----	-----	25	-----	-----	13
measurement of	-----	-----	-----	-----	-----	-----

Noise

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Noise (continued)						
sources of	-----	-----	27	-----	-----	-----
Noise-reduction studies	-----	-----	82, 166, 171, 179	-----	-----	-----
Nondispersive infrared	58	-----	-----	-----	-----	-----
Nonfossil energy substitution	226, 228	-----	-----	-----	-----	-----
Nonfossil fuels	11, 77, 78, 202, 224, 292	-----	-----	-----	-----	-----
prices of	226	-----	-----	-----	-----	-----
Noosphere	205, 300	-----	-----	-----	-----	-----
North America	-----	129, 130, 132, 245, 247, 251, 343	64, 119, 121, 130, 132	-----	-----	-----
snow cover changes in	-----	-----	-----	-----	-----	38
North Atlantic	-----	-----	123, 126	-----	-----	16, 19, 104
North Atlantic drift	-----	-----	-----	-----	-----	137
North Atlantic Study	-----	-----	-----	-----	-----	129
North Carolina State University	-----	-----	-----	179	-----	-----
North Ellesmere Ice Cap	-----	-----	-----	-----	-----	23, 146
North Pacific Experiment	92	-----	-----	-----	-----	-----
Northern Ecosystem Carbon Simulator	-----	-----	-----	142-144	-----	-----
Northern Hemisphere	190	9, 18, 61, 130, 132, 207, 218, 244	-----	-----	13	-----
average temperature data for	-----	-----	59-61, 64, 66	-----	-----	-----
dynamic height of oceans in	-----	-----	103	-----	-----	-----
pressure data for	-----	-----	40-41	-----	-----	-----
rainfall records for	-----	-----	152, 159	-----	-----	-----
snow and ice cover of	-----	-----	111-112, 116, 119, 120, 173	-----	-----	-----
temperature variations of	-----	-----	63, 65, 70, 99	-----	-----	-----
tropospheric temperatures for	-----	-----	69	-----	-----	-----
volcanic eruptions in	-----	-----	44	-----	-----	-----
Northern high latitude seas	93	-----	-----	-----	-----	-----
Norway	-----	-----	34, 42	-----	-----	-----
Norwegian Antarctic Research Expedition	-----	-----	-----	-----	-----	211
Norwegian Sea	20, 94	-----	-----	-----	125	-----
Novaya Zemlya	-----	-----	-----	-----	-----	141
Nuclear energy	71, 78, 79, 230, 258, 259	-----	-----	-----	-----	-----
Nuclear testing (see also Tritium)	36, 91, 93-94, 99, 105, 153, 156, 204, 299	217, 221	-----	-----	-----	129
Nuclear war	202, 297	211, 212	-----	-----	-----	-----
Nutrient availability	-----	-----	-----	xxi, 125, 132, 135, 138, 140, 145, 147, 148, 165, 173, 211	-----	-----
Nutrient cycling	-----	-----	-----	24, 135, 193	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Nutrient deficiencies: mineral	-----	-----	-----	72, 128, 175, 198	-----	-----
Nutrient exhaustion of the oceans	-----	-----	-----	-----	116	-----
Nutrient retention in soil	-----	-----	-----	132, 212	-----	-----
Nutrient strength	-----	-----	-----	159	-----	-----
Nutrient stress in plants interaction of with carbon dioxide concentration (see also Carbon dioxide concentration)	-----	-----	-----	113 21, 111, 128	19	-----
Nutrient transport by plants	-----	-----	-----	-----	75	-----
Nutrient uptake capacity	-----	-----	-----	113, 133, 209, 211	-----	-----
Nutrients	88, 95, 96, 105, 106, 143, 170, 204, 298	-----	-----	-----	-----	-----
accumulated cycling of oceanic:	188 148, 258, 264	-----	-----	-----	-----	-----
availability of depletion of: turbulence effects on supply of soil: availability of	-----	-----	-----	-----	19	-----
Nutrition: effects of fisheries on effects of food production on human	-----	-----	-----	-----	173 195	-----
mineral	-----	-----	-----	18, 87	xviii, 6, 173, 175, 195, 200, 212, 217, 218	-----
Nutrition and disease	-----	-----	-----	-----	195-201	-----
Nyctoperiods	-----	-----	-----	15	-----	-----

O

Oak	-----	-----	-----	162	-----	-----
Oak Ridge National Laboratory	241	-----	-----	-----	-----	-----
Oasis effect	-----	-----	-----	83	-----	-----
Oats	-----	-----	-----	-----	75	-----
Observational records	-----	261	181-182, 183	-----	-----	-----
Ocean buoys	-----	-----	182	-----	-----	-----
Ocean-atmosphere coupling	-----	276	-----	-----	-----	-----

Ocean-atmosphere exchange

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ocean-atmosphere exchange	v, xviii, 7, 9, 19, 45, 48, 49, 57, 84-87, 92-93, 95, 100, 106, 133, 143, 146, 187, 254, 274-275, 295-296	-----	-----	-----	-----	-----
Ocean-atmosphere interactions	-----	-----	v, 112	v	-----	-----
Ocean-atmosphere turbulent heat flux	-----	-----	124	-----	-----	-----
Ocean chemistry	30, 36, 56, 85-89, 271	-----	-----	-----	-----	-----
Ocean circulation (see also Oceans, circulation of)	83-84, 88, 105, 150, 258, 280	185, 262	83, 97, 101, 102, 172, 184	-----	-----	-----
changes of	-----	-----	85, 96, 172, 173	-----	-----	-----
deep water injection and	257	-----	-----	-----	-----	-----
influence of on climate	-----	-----	85	-----	-----	-----
models of	-----	-----	105	-----	-----	-----
shifts in	-----	-----	166	-----	-----	-----
Ocean composition	84	-----	-----	-----	-----	-----
Ocean Continental Shelf Environmental Program	-----	-----	-----	-----	137, 138	-----
Ocean currents	21, 84, 299	63, 72, 262, 276	101, 171, 183	-----	97, 100, 102, 103, 111, 113, 114-116, 123, 124, 125, 126, 128, 130, 131, 132, 134, 135, 139	-----
density-driven	-----	-----	-----	-----	116	-----
effects of	-----	-----	-----	-----	109	-----
energetic deep	-----	-----	-----	-----	123	-----
heat transport by	-----	61, 107, 161, 179	-----	-----	201	-----
measurements of	-----	-----	-----	-----	101, 103, 117, 121, 127, 139	-----
shifts in	-----	-----	-----	-----	121	-----
subsurface	-----	-----	-----	-----	97	-----
upper	-----	-----	-----	-----	214	-----
wind-driven	-----	-----	-----	-----	-----	-----
Ocean density analyses of	83	-----	101-104, 172	-----	-----	-----
geographic distribution of data on	-----	-----	103	-----	-----	-----
structure of	-----	-----	103	-----	-----	-----
-----	-----	-----	95	-----	-----	-----
Ocean dynamics	146	185	-----	-----	-----	-----
effects on climate of	-----	21, 63, 107	-----	-----	-----	-----
internal	-----	21, 184, 267	-----	-----	-----	-----
Ocean gyres	84, 93, 180, 205	-----	-----	-----	-----	-----
Ocean oscillations	202	-----	-----	-----	-----	-----
Ocean sources and sinks	xviii, 10, 47-48, 52, 83, 105, 144, 251	-----	-----	-----	-----	-----
Ocean surface stratification	-----	-----	-----	-----	114	-----
Ocean surveys	91-92	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Oceanic carbon dioxide:						
fluxes of	45, 83-107	-----	-----	-----	-----	-----
seasonal oscillations of	167	-----	-----	-----	-----	-----
Oceanic plates	-----	-----	-----	-----	-----	82
Oceanographic parameters:						
physical	-----	-----	-----	-----	129	-----
Oceanography	-----	-----	-----	-----	-----	201-203
Oceans (see also Deep oceans; Deep water)	7-8, 180, 251, 300	xxi	183	-----	11	-----
Oceans:						
absorption of radiation by	-----	-----	96	-----	-----	-----
air and sea temperature	-----	159	-----	-----	-----	-----
differences over						
biological chemistry of	88, 105	-----	-----	-----	-----	-----
carbon in the						
bottom topography of	-----	-----	-----	-----	113	-----
bottom water temperatures of	-----	-----	-----	-----	114, 120, 124, 129, 130	-----
carbon dioxide-induced	-----	-----	-----	-----	-----	62
warming of						
carbon dioxide uptake by	xviii, xx, 5, 6, 18, 145, 147, 154, 156, 158-159, 167, 251, 254, 257, 258, 262, 269, 280, 296	-----	-----	-----	-----	-----
carbon distribution in	6, 34, 84	-----	-----	-----	-----	-----
carbon turnover in	154	-----	-----	-----	-----	-----
circulation near ice	-----	-----	-----	-----	-----	4, 5
shelves of						
circulation of (see also	xviii, xx, 7, 49, 84, 101, 103, 258, 295-296	-----	-----	-----	117, 154	66, 276, 317
Ocean circulation)						
climate-induced changes in	-----	-----	-----	-----	-----	316
polar region						314
vertical						277
convective overturning of	-----	-----	-----	-----	102	-----
water column of						
cooling of	-----	-----	-----	-----	-----	49, 269, 271-272
currents of						7
data coverage of	-----	-----	xxii, 97, 169, 171	-----	-----	-----
deep	7, 83-84, 104, 106	-----	-----	-----	-----	-----
deep water formation in	105, 150, 258	-----	-----	-----	-----	-----
density gradients in	-----	178	-----	-----	-----	-----
density of (see Ocean						
density)						
depth of the surface layer of	83, 154	-----	-----	-----	-----	-----
direct ventilation of	150	-----	-----	-----	-----	-----
dissolved oxygen in	-----	-----	-----	-----	-----	130-133
downward vertical mixing in	-----	77	-----	-----	-----	-----
downwelling in	84-85	158	-----	-----	-----	-----
dynamic height of	-----	-----	103	-----	-----	-----
effects on atmospheric	-----	-----	171	-----	-----	-----
conditions of						
equilibrium temperature	-----	271	-----	-----	-----	-----
response of						
fixed nitrogen inputs of	97	-----	-----	-----	-----	-----
flow patterns of	104, 151	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Oceans (continued)						
freshwater flux of:						
measurement of (see also Sea water, freshening of)	-----	-----	-----	-----	-----	20
freshwater sources of	-----	-----	-----	-----	102, 103, 109	-----
heat flux of	-----	-----	182	-----	-----	-----
heat storage of	-----	8, 21, 151, 154, 160, 169, 268, 271, 326	115, 171, 174	-----	-----	-----
heat transport in	-----	xxv, 72, 90, 113, 144, 157, 158, 161, 179, 185, 268, 276	-----	-----	-----	5, 66, 120, 267
hemispheric average temperatures of	-----	-----	96-100	-----	-----	-----
inorganic carbon in	7	-----	-----	-----	-----	-----
interactions of with ice shelves	-----	-----	-----	-----	-----	5, 66
internal feedback processes of	-----	173, 182	-----	-----	-----	-----
internal mixing rates	-----	162	-----	-----	-----	-----
internal structure of	98	-----	-----	-----	-----	-----
kinetic energy of	-----	178	-----	-----	-----	-----
layering of	-----	8, 184, 267	-----	-----	-----	-----
long-term climate change of	-----	-----	93	-----	-----	-----
mass of water in (see also Oceans, volume of)	-----	-----	-----	-----	-----	92, 99
mathematical models of (see also Models, ocean circulation)	97	-----	-----	-----	-----	-----
meltwater input of	-----	-----	-----	-----	-----	13, 86
mixed-layer temperatures of	-----	-----	168	-----	-----	-----
moderating influence of	-----	60	-----	-----	-----	-----
nutrient content of	33, 103	-----	-----	-----	-----	-----
organic carbon in	7, 96, 188	-----	-----	-----	134	-----
overturning of	92, 103, 105, 106	-----	-----	-----	-----	-----
pH of	-----	-----	-----	-----	xiv, 100, 131, 132, 134, 137	-----
changes in	-----	-----	-----	-----	xiv, 100, 103-105, 130	-----
photosynthesis-respiration cycles of	148	-----	-----	-----	-----	-----
plant primary productivity of	-----	-----	-----	181	-----	-----
productivity of	9, 180	-----	-----	180	-----	-----
projections of	-----	-----	-----	-----	-----	6, 86
temperatures of	-----	-----	-----	-----	-----	-----
properties of	-----	-----	-----	-----	xv, 97, 113, 125	-----
measurement of	-----	-----	-----	-----	-----	124
response times of	-----	xxii, 8	-----	-----	-----	-----
response to increasing carbon dioxide of	-----	-----	171	-----	-----	-----
salinity of	10, 83, 85, 90, 95, 105	-----	xxiii, 93, 96, 101, 102, 104, 171, 172, 182	-----	100, 102, 103, 114, 116, 120, 125, 128, 130, 131, 132, 134, 213	-----
measurements of	-----	-----	101	-----	-----	-----
time series of	-----	-----	101, 175	-----	-----	-----
salinity versus density of	-----	-----	-----	-----	-----	131
seasonal lag of	-----	72	-----	-----	-----	-----
temperatures of	-----	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Oceans (continued)						
sequestering of heat by						
Southern Hemisphere			104, 152			
stability of					100, 101, 120,	
212, 213						
stabilizing influence on			xxii, 96, 165			
global climate of						
subsurface temperatures of			xxiii, 97, 100,			
surface layers of	7, 83, 274		104, 172			
freshening of (see also)						
Sea water, freshening of)					131, 134	
surface mixed layer of		61, 154, 160, 267				
surface salinity of		63, 77				
surface temperatures of		206				2, 59
surface warming of						2, 48
temperature and current			101			
interactions of						
temperature distribution of		72			102	
temperatures of	10, 83, 90, 105,	63, 180, 181	93, 99, 183		102, 108, 119,	2, 65, 106
	255, 274, 296				122, 212.	
changes in			172			
fluctuations in					111, 120, 125,	
					128, 130, 131,	
					132, 139	
					27	
lag behind air						
temperature of						
variations in						
thermal diffusivity of						108, 114
thermal expansion of			xxiii, 96-97,			270
			172, 174			ix, 1, 2, 10, 12,
						15-19, 41, 59-61,
						64, 65, 73, 93,
						104
thermal inertia of		8, 21, 175, 242,				
		262, 268, 276				
thermal response time of		8, 20, 21, 102,				
		162, 175, 242,				
		262, 268, 276, 277				
thermal storage of and		90, 178, 185				
transport by						
thermal variability of						
thermocline of	7	61, 144, 170,				104-115
		171, 184				
trace metals in					100, 137	
tracer data on						
tracers in (see also)						
Tracers; Transient Tracers						
in the Ocean)						
tropical	48				108	
turbulence in					97, 101, 102,	
					108-109, 111,	
					114-116, 123,	
					124, 125, 128,	
					130-132, 134,	
					135, 139, 212,	
					214, 215	
turbulent mixing of		179, 180				
upwelling in		19, 41, 48, 49,				
		50, 52, 53,				
		84-85, 92, 95,				
		148, 150, 156,				
		179, 191				

Oceans

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Oceans (continued)						
ventilation of vertical eddy diffusivity in vertical mixing of	101, 169, 192	-----	158, 171, 178, 181	-----	-----	-----
vertical stability of surface waters of vertical transport in volume of (see also Oceans, mass of water in)	9, 20, 98, 146, 274, 296	-----	-----	-----	114	-----
changes in warming of	-----	-----	-----	-----	102	-----
warming of air and wind-induced turbulence in	159	-----	104, 166, 172	-----	101	12, 59-60, 93, 104 269, 271-272
77	-----	-----	-----	-----	-----	-----
Ogallala Aquifer	-----	-----	-----	-----	82	-----
Oil combustion: emissions from	66-67	-----	-----	-----	-----	-----
Oil embargo	xvii, xx, 11, 19, 277-278, 281	-----	-----	-----	-----	-----
Oil price	67	-----	-----	-----	-----	-----
Okhotsk Sea	-----	-----	-----	-----	125	-----
Okra	-----	-----	-----	74, 87, 188	-----	-----
Oleander	-----	-----	-----	122	-----	-----
Open-air field releases (see Free-air field releases)						
Optical depth definition	45, 46, 168	-----	-----	-----	-----	-----
Optical depth of the aerosol layer	45	-----	45	-----	-----	-----
Orbit of Earth: eccentricity of	202	-----	-----	-----	-----	-----
Orbital Mapping System	-----	-----	-----	-----	-----	235
Orbital parameters	-----	-----	4, 6, 134	-----	-----	-----
Order of dominance	-----	-----	-----	166	-----	-----
Organic carbon: accumulation in the deep ocean of forest	96-97	-----	-----	-----	-----	-----
global flux from rivers of oceanic soil	95	-----	-----	-----	147	-----
117-118, 122, 126, 134	-----	-----	-----	-----	134	-----
terrestrial	8, 134, 179	-----	-----	-----	-----	-----
Organic matter accumulation	-----	-----	-----	24	-----	-----
Organization of Petroleum Exporting Countries	67	-----	-----	-----	-----	-----
Organs: development of plant	-----	-----	-----	66, 81, 82, 86	-----	-----
Osmoregulation	-----	-----	-----	74	-----	-----
Osmotic adjustment capability	-----	-----	-----	113	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Outcropping isopycnal horizons	155	-----	-----	-----	-----	-----
Outflow glacier velocities: measurements of	-----	-----	-----	-----	-----	172-173
Overfishing	-----	-----	-----	-----	107, 124, 127	-----
Overgrazing	180	-----	-----	-----	44, 79	-----
Overland flow of water	-----	-----	-----	198	-----	-----
Overriding crust	-----	-----	-----	-----	-----	82
Overshoot phenomenon	294	-----	-----	-----	-----	-----
Overstory trees	-----	-----	-----	176	-----	-----
Overwintering of pests	-----	-----	-----	-----	86	-----
Oxygen oceanic dissolved	95, 152, 203	-----	-----	70	-----	130-133
Oxygen-18: glacial spiking with shelfwater concentration of	-----	-----	-----	-----	-----	121
-----	-----	-----	-----	-----	-----	122
Oxygen-18 record	-----	-----	-----	-----	-----	150
Oxygen cycle	293	-----	-----	-----	-----	-----
Oxygen demand	194	-----	-----	-----	-----	-----
Oxygen distribution	99	-----	-----	-----	-----	-----
Oxygen isotope data	-----	250	64	-----	-----	151, 152, 190, 191, 202
Oysters	-----	-----	-----	-----	128	-----
Ozone	146, 165, 202, 242, 293	xix, 3, 5, 37, 40, 51, 193, 195, 205, 208, 217-218, 263, 268-269	16, 23, 24, 167, 183	xix, 75, 209, 212	-----	-----
absorption bands of	-----	29, 262	-----	-----	-----	-----
absorption of UV radiation by	-----	208	-----	-----	-----	-----
atmospheric sources of	-----	208	-----	-----	-----	-----
calculated and observed trends of distribution of	-----	208, 217-218	-----	-----	-----	-----
destruction of	-----	208, 269	-----	-----	-----	-----
distribution of in troposphere	-----	196, 197	-----	-----	-----	-----
geographic distribution of	-----	224	-----	-----	-----	-----
longwave radiative effects of	-----	30, 31, 51	-----	-----	-----	-----
solar absorption by	-----	31, 40, 208	-----	-----	-----	-----
solar and thermal effects of	-----	208	-----	-----	-----	-----
stratospheric concentrations of	-----	xxii, 198, 205	-----	-----	-----	-----
surface temperature	-----	209, 210, 220-221	-----	-----	-----	-----
sensitivity to perturbations of	-----	-----	-----	-----	-----	-----

P

Pacific hake	-----	-----	-----	-----	119	-----
Pacific Ocean	34, 49, 50, 52-53, 91, 93,	131	97, 152	-----	97, 111, 114, 115, 117, 119,	197

Pacific Ocean

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Pacific Ocean (continued)	95, 101, 148, 167, 191	-----	-----	-----	122, 125, 134-136, 137, 139	-----
Pack ice	-----	-----	-----	-----	-----	121
disappearance of	-----	-----	127	-----	-----	-----
long-term stability of	-----	-----	128	-----	-----	-----
summer retreat of margin of	-----	-----	127	-----	-----	-----
Paleoclimatic data goals in assembling sets of testing by GCMs of	-----	247, 248, 253 246	-----	-----	-----	-----
Paleoclimatic record	-----	252	-----	-----	-----	-----
Paleoclimatologic reconstructions	-----	-----	5	-----	-----	36, 220
Paleoclimatology	-----	241	-----	-----	-----	-----
Paleoecological records	-----	-----	-----	-----	152, 161	-----
Paleoglaciologic studies	-----	-----	-----	-----	-----	36, 220
Paleosols	181, 186, 296	-----	-----	-----	-----	-----
Paleozoic Era	192, 200	-----	-----	-----	-----	-----
Paludification	197	-----	-----	-----	-----	-----
Panuliris series	-----	-----	-----	-----	-----	16, 17, 18, 104-115
Panuliris steric height	-----	-----	-----	-----	-----	112, 113
Parameter sensitivities	-----	354-357	-----	-----	-----	-----
Parameterization definition	-----	347	-----	-----	-----	-----
longwave-radiation subgrid-scale process validation of	-----	12 33-39 67-69 143, 360	-----	-----	-----	-----
Parasites	-----	-----	-----	-----	xvi, 194	-----
control of fish	-----	-----	-----	-----	197	-----
hosts of human	-----	-----	-----	-----	105, 125, 131, 132, 134, 140	-----
resistance of animals to vector-borne vectors of	-----	-----	-----	-----	194, 199 200, 212, 213, 214, 216	-----
Parasitic diseases	-----	-----	-----	-----	76	-----
climate effects on	-----	-----	-----	-----	213	-----
Partitioning of dry matter	-----	-----	-----	113	-----	-----
Paspalum	-----	-----	-----	126	-----	-----
Passive microwave remote sensing	-----	-----	-----	-----	-----	39
Past climates: study of	-----	xvii, 239-253, 261, 278, 279, 325	-----	-----	-----	-----
Past climatic change: role of carbon dioxide in	-----	239-241	-----	-----	-----	-----
Pasture	122, 127, 134	-----	-----	134, 140	72	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Patagonian Andes	-----	-----	-----	-----	-----	143
Patagonian ice caps	-----	-----	-----	-----	-----	2, 60, 143
Pathogens	-----	-----	-----	102, 182, 199, 201, 210, 212	-----	-----
Pathogens of humans	-----	-----	-----	-----	xvi, 199	-----
airborne	-----	-----	-----	-----	190-192, 213, 214	-----
Pathogens of trees	-----	-----	-----	-----	155, 156, 159, 161, 212, 214	-----
Peanuts	-----	-----	-----	-----	72	-----
Peas	-----	-----	-----	70, 195	-----	-----
Pease River	-----	-----	-----	-----	35	-----
Peat	xix, 8, 9, 115, 117, 122, 179, 181, 186, 192, 197, 271, 291, 296	-----	-----	xxii, 138	-----	-----
Pelagic detritus food supply	-----	-----	-----	-----	121	-----
Penetrative convection	-----	137, 143	-----	-----	-----	-----
People's Republic of China	71	-----	38, 45, 64, 131, 132, 159, 160	-----	90, 97	-----
Percolation of water through soil	-----	-----	-----	-----	26	-----
Perihelion: time of	-----	xxii, 252	-----	-----	-----	-----
Permafrost	-----	-----	111, 130-133, 138, 139, 173	xix, xxii, 137, 138	-----	241-246
changes in definition	-----	-----	-----	-----	-----	36-39, 246
effects on climate on extent of	-----	-----	130-131	-----	-----	-----
ice content of	-----	-----	132	-----	-----	39, 241, 246
melting of	-----	-----	131	-----	-----	39, 246
northward displacement of boundary of	-----	-----	131-132	-----	-----	-----
observations of relic	-----	-----	132	-----	-----	-----
retreat of	57, 297	-----	-----	-----	-----	-----
sensitivity to climatic warming of	-----	-----	133	-----	-----	-----
subsea temperatures of	-----	-----	131	-----	-----	-----
thawing of	-----	-----	-----	-----	-----	39, 246
thawing rates of	-----	-----	133	-----	-----	243
thermal stability of	-----	-----	-----	-----	-----	-----
thickness of	-----	-----	131	-----	-----	216
water content of zones of	-----	-----	131, 132	-----	-----	39, 241, 243, 246
39	-----	-----	-----	-----	-----	-----
Permanent Service on the Fluctuations of Glaciers	-----	-----	-----	-----	-----	34, 42, 140, 228
Permo-Carboniferous periods	192	-----	-----	-----	-----	-----
Perturbation technique	-----	34	-----	-----	-----	-----
Perturbed state: definition	-----	14	-----	-----	-----	-----

Pest control

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Pest control	-----	-----	-----	xxi, 191	-----	-----
Pest losses of trees	-----	-----	-----	198	-----	-----
Pest management	-----	-----	-----	-----	83-85, 86, 88, 90	-----
Pest monitoring	-----	-----	-----	-----	85	-----
Pest reports: computerized	-----	-----	-----	-----	85	-----
Pesticides	-----	-----	-----	-----	44, 72	-----
Pests agricultural	-----	-----	-----	-----	xvi, 80, 84, 193	-----
effect on carbon cycling of effects of changing climate on geographic distribution of management of migration of natural control factors of poleward extension of reproduction of	199, 257	-----	-----	-----	84	-----
Petroleum (see also Oil): unconventional sources of pH changes in seawater	75	-----	-----	-----	xiv, xvii, 100-102, 103-105, 130	-----
Phalaris	-----	-----	-----	126	-----	-----
Phasey bean	-----	-----	-----	-----	85	-----
Phenolics: soluble	-----	-----	-----	208	-----	-----
Phenology	-----	-----	-----	24, 127, 134, 140, 157, 162, 208	-----	-----
Phloem loading	-----	-----	-----	39, 133	-----	-----
Phlox	-----	-----	-----	160	-----	-----
Phosphate: inorganic	-----	-----	-----	58, 122	-----	-----
Phosphorus	88, 90, 105, 152, 170, 300	-----	-----	xxv, 75, 113, 188, 190, 191, 201	-----	-----
deficiency of fixation of	-----	-----	-----	75	-----	-----
-----	-----	-----	-----	75	-----	-----
Phosphorus cycle	9, 203, 293, 299	-----	-----	-----	-----	-----
Phosphorylated compounds	-----	-----	-----	58	-----	-----
Photochemical oxidants	266	-----	-----	-----	-----	-----
Photographic records of glaciers	-----	-----	-----	-----	-----	frontispiece, 147, 233
Photoperiods	-----	-----	-----	13, 15	-----	-----
Photorespiration	118-119, 190	-----	-----	5, 55, 73, 102, 114, 120, 178, 207, 212	150	-----
Photosynthate composition	-----	-----	-----	5	-----	-----
Photosynthate concentration	-----	-----	-----	5	-----	-----
Photosynthate production	-----	-----	-----	14, 129	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Photosynthate translocation (see also Translocation)	-----	-----	-----	5, 133	-----	-----
Photosynthesis	19, 20, 21, 55, 105, 118-119, 131-132, 143, 177, 190, 200, 201, 300	-----	-----	ix, xxi, 3, 5, 19, 25, 61, 82, 102, 119-125, 158, 162, 169, 207	3, 19, 101, 134, 135	-----
C3 pathway to	-----	-----	-----	-----	28	-----
C4 pathway to	-----	-----	-----	-----	28	-----
correlation of starch	-----	-----	-----	59	-----	-----
content with	-----	-----	-----	-----	-----	-----
definition	-----	-----	-----	56	-----	-----
enhanced	4, 54-55	-----	-----	-----	75	-----
inhibition of	-----	-----	-----	58, 59, 69, 85, 90, 121, 125, 126, 127, 130, 141, 142, 145, 208	-----	-----
kinetic properties of	-----	-----	-----	13	-----	-----
leaf	-----	-----	-----	xxi, 59, 60, 65, 128-129, 174	-----	-----
mechanistic changes in	-----	-----	-----	13	-----	-----
optimum temperature for	-----	-----	-----	72, 208	-----	-----
Photosynthetic capacity	-----	-----	-----	134	-----	-----
Photosynthetic efficiency	-----	-----	-----	65, 69	-----	-----
Photosynthetic rate	-----	-----	-----	3, 55, 57, 58, 69, 72, 76, 78, 80, 82, 83, 84, 85, 87, 120, 121, 122, 123, 124, 126, 127, 139, 141, 142, 143, 144, 148, 157, 174, 198	75, 103	-----
crop canopy	-----	-----	-----	xviii, 56, 60, 61, 64, 65, 187	-----	-----
global	-----	-----	-----	180	-----	-----
leaf-area basis of	-----	-----	-----	56, 157, 187	-----	-----
Photosynthetic responses:	-----	-----	-----	123	-----	-----
variations of in native	-----	-----	-----	-----	-----	-----
species	-----	-----	-----	-----	-----	-----
Photosynthetic uptake	xvii, 53	-----	-----	-----	-----	-----
Photovoltaics	71, 228	-----	-----	-----	-----	-----
Phreatophytes	-----	-----	-----	-----	39	-----
definition	-----	-----	-----	-----	59, 217	-----
Physics Institute of the	28	-----	-----	-----	-----	-----
University of Bern	-----	-----	-----	-----	-----	-----
Physiological responses (see	-----	-----	-----	6, 55, 114, 132, 157, 175, 182	-----	-----
also Whole plant ...)	-----	-----	-----	-----	-----	-----
Physiological tolerance	-----	-----	-----	-----	111	-----
limits of subpolar fish	-----	-----	-----	-----	-----	-----
Physiology:	-----	-----	-----	-----	86	-----
animal and crop	-----	-----	-----	-----	173, 175, 177	-----
human	-----	-----	-----	-----	-----	-----
Phytophthora infestations	-----	-----	-----	-----	84	-----

Phytoplankton

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Phytoplankton	97	-----	-----	-----	xiv, 97, 100, 105, 124 97, 116, 218	-----
production of species composition of turbulence effects on	-----	-----	-----	-----	109, 116, 118 101, 108	-----
Phytorhizotrons	-----	-----	-----	60	-----	-----
Phytotrons	-----	-----	-----	-----	xviii, xix, xx, 13, 18, 26, 28, 74, 133	-----
Piedmont	-----	-----	-----	160	-----	-----
Pigweed	-----	-----	-----	131, 158, 162	-----	-----
Pine Island Bay	-----	-----	-----	-----	-----	325
Pine Island Glacier	-----	-----	-----	-----	-----	33, 53, 206-207, 279-282, 301, 302, 315
Pineapple	-----	-----	-----	-----	75	-----
Pink shrimp	-----	-----	-----	-----	112, 118, 123-124, 129, 139	-----
Pinto beans	-----	-----	-----	75	-----	-----
Pioneer Hybrid International	-----	-----	-----	188	-----	-----
Plague	-----	-----	-----	-----	193	-----
Plaice	-----	-----	-----	-----	107	-----
Planck function	-----	32, 40, 43, 208	-----	-----	-----	-----
Planetary albedo effects of aerosols on effects of clouds on	-----	88, 199, 289, 316 47, 199 306, 310, 311	-----	-----	-----	-----
Planetary boundary layer behavior of	-----	276 xxii, 77	-----	-----	-----	-----
Planetary radiation balance	300	-----	-----	-----	-----	-----
Planetary rotation (see also Earth, rotation of the; Rotational response), acceleration of	-----	-----	-----	-----	-----	34, 101, 102
Planetary viscosity	-----	-----	-----	-----	-----	94
Planetary waves	-----	207	-----	-----	-----	-----
Plankton (see also Phytoplankton; Zooplankton)	180	-----	-----	-----	-----	-----
Plankton growth of	-----	-----	-----	-----	101, 113, 129, 131, 135 108, 110, 127, 136, 217	-----
species composition of	-----	-----	-----	-----	103, 212	-----
Planktonic food supplies	-----	-----	-----	-----	105, 108, 133, 139, 140, 212, 217, 218	-----
Plant-animal interactions	-----	-----	-----	119, 139, 140, 169	-----	-----
Plant community: composition of interactions of	-----	-----	-----	119, 157, 169 xxiii, 7, 157	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Plant-geographic data needs	-----	-----	-----	-----	158	-----
Plant growth secondary effects on	-----	-----	-----	5,7	19, 108	-----
Plant growth and reproduction: changes in	-----	-----	-----	6, 132, 137	-----	-----
Plant-growth variables: interactions of	-----	-----	-----	57, 101	-----	-----
Plant relative yield	-----	-----	-----	162	-----	-----
Plant residue management	-----	-----	-----	193	-----	-----
Plant response	-----	-----	-----	ix, 3, 36, 56	-----	-----
Plant sink strength	-----	-----	-----	73, 145	-----	-----
Plant succession	-----	-----	-----	-----	150	-----
Plant water status	-----	-----	-----	xxv, 5, 193	-----	-----
Planting times	-----	-----	-----	-----	79, 86	-----
Plants:						
ages of	-----	-----	-----	67	-----	-----
alpine	-----	-----	-----	132	-----	-----
annual	-----	-----	-----	70, 104, 129, 134, 138, 147, 161, 162, 168, 187, 188-189, 210	-----	-----
aquatic	-----	-----	-----	-----	xiv, 19, 39, 44, 55, 59, 217	-----
architecture of	-----	-----	-----	43	-----	-----
atmospheric pollutant	-----	-----	-----	5	-----	-----
tolerance of	-----	-----	-----	43	-----	-----
branching patterns of	-----	-----	-----	200	-----	-----
breeding of	-----	-----	-----	128	-----	-----
death of	-----	-----	-----	192	-----	-----
disease resistance of	-----	-----	-----	159	-----	-----
early development of	-----	-----	-----	28	-----	-----
geographic range of	-----	-----	-----	4	-----	-----
growth enhancement of	-----	-----	-----	5, 208	-----	-----
growth forms of	-----	-----	-----	xxi, 5, 67, 127-132, 182	-----	-----
growth rate of	-----	-----	-----	193, 200	-----	-----
growth regulators of	-----	-----	-----	145, 146, 201	-----	-----
lifespan of	-----	-----	-----	58	-----	-----
metabolites of	-----	-----	-----	xxii, 70, 104, 123, 129, 134, 135, 137, 145, 147, 160, 182, 187, 189, 198, 210, 211	-----	-----
perennial	-----	-----	-----	199	-----	-----
physiology of	179	-----	-----	82	-----	-----
population of	-----	-----	-----	xxi, 14, 128, 140, 142, 157, 176, 192, 193, 195, 197, 201, 210, 212	25	-----
productivity of	144	-----	-----	199	-----	-----
quality of	-----	-----	-----	-----	45, 59	-----
salt tolerance of	-----	-----	-----	-----	-----	-----
seasonal cycle of growth	-----	18, 62	-----	-----	-----	-----

Plants

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Plants (continued)						
seedling stage growth of senescence of	-----	-----	-----	129, 141 43, 128, 134, 161, 208	-----	-----
short-life-cycle species response to carbon dioxide of	-----	-----	-----	189	19, 55, 75	-----
survival of vascular	200	-----	-----	66	-----	-----
weight of	-----	-----	-----	157	-----	-----
Plastids damage	-----	-----	-----	121	-----	-----
<i>Platanus occidentalis</i>	-----	-----	-----	158	-----	-----
Pleistocene Epoch	184, 192, 202	-----	-----	-----	80	-----
Pleistocene glaciation cycles	-----	-----	-----	-----	97	-----
Pleistocene ice sheets: loss of	-----	-----	-----	-----	-----	3, 12, 14, 28, 46, 61
Pneumonia	-----	-----	-----	-----	181	-----
Pod fill	-----	-----	-----	68	-----	-----
Podzolics	-----	-----	-----	-----	80	-----
Poland	-----	-----	-----	-----	34	-----
Polar bears	-----	-----	-----	-----	105	-----
Polar caps melting of	-----	-----	173 104, 172	-----	-----	-----
Polar ice	11, 55, 102	-----	-----	35	-----	-----
Polar outcrop	148, 151	-----	-----	-----	-----	-----
Polar regions warming of	85	-----	-----	-----	54, 154	321
Polar wander	-----	-----	-----	-----	-----	3, 34, 61, 92, 94, 97, 98, 99, 100, 101, 102, 143
Poleward amplification of climate variables	-----	-----	-----	-----	-----	48, 62, 92, 241
Policies:						
carbon dioxide abatement	12	-----	-----	-----	-----	-----
Policy issues	xxii, 21, 217, 227-230, 243, 281	ix, 169, 174, 175	180	x	vii, xiii, 211	-----
agricultural	-----	-----	-----	-----	71, 88-89	-----
Pollen data	-----	247, 269	-----	-----	-----	-----
Pollen production and dispersal: meteorological effects on	-----	-----	-----	-----	192, 199, 213	-----
Pollen records	-----	-----	-----	-----	159	-----
Pollination	-----	-----	-----	xxiii, 139-140, 210	-----	-----
Pollination relationships	-----	-----	-----	160	-----	-----
Pollock	-----	-----	-----	-----	106-107, 112, 119, 120-121, 123, 129, 139	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Pollutants	202, 263, 280	-----	-----	xxi, 75, 209, 212	-----	-----
Pollution	-----	46	-----	-----	-----	-----
Pollution control	-----	-----	-----	-----	38	-----
Pollution stresses	-----	-----	-----	-----	128, 155	-----
Polychaetes	-----	-----	-----	-----	107, 124	-----
Polygonum pensylvanicum	-----	-----	-----	131, 162, 158	-----	-----
Polynya	258	-----	125	-----	-----	-----
Ponds: farm	-----	-----	-----	-----	82	-----
Poplar	-----	-----	-----	75	-----	-----
Population growth of	xxiii, 27 18, 65, 79, 129, 224, 230, 237, 240, 251, 258, 266, 267	-----	-----	-----	-----	-----
Population fluctuations and lifespans of fish	-----	-----	-----	-----	113	-----
<i>Populus deltoides</i>	-----	-----	-----	158	-----	-----
Pore-fluid removal	-----	-----	-----	-----	-----	74
Potassium	-----	-----	-----	190, 191	-----	-----
Potassium deficiency in plants	-----	-----	-----	87	-----	-----
Potato	-----	-----	-----	xxi, 75, 103, 105-109, 130, 235, 236	-----	-----
Potato blight	-----	-----	-----	-----	84	-----
Power density spectra	-----	-----	-----	-----	-----	112, 113
Prairie forest border	-----	249, 251	-----	-----	-----	-----
Precipitation	-----	xxii, 61, 64, 68, 276, 343	181	63, 76, 77, 81, 138	xiv, xv, 74, 113, 198-200, 213	138, 139, 143, 217
annual average variations in	-----	-----	153	-----	-----	-----
Antarctic	-----	-----	154-155, 157-158	-----	-----	47, 63
averaging method for carbon dioxide-induced effects on	-----	-----	152	-----	-----	-----
carbon dioxide-induced increase in	-----	-----	40	-----	-----	-----
changes in (see also Precipitation variations)	-----	90, 93-94, 130-132, 267	xxv, 134, 166, 173, 175	-----	82, 102, 162, 165	-----
geographic distribution of	-----	99, 104, 119, 122, 123, 141	-----	-----	-----	-----
long-term simulated geographic distribution of	-----	93, 131	151-161	-----	-----	-----
simulated latitude-time cross section of	-----	98, 132	-----	-----	-----	-----
changes in evaporation and	-----	132-133	-----	-----	-----	-----
changes in tropical	-----	131	-----	-----	-----	-----
changes in zonal means of	-----	93	-----	-----	-----	-----
climatology of convective	-----	136	-----	-----	-----	-----

Precipitation

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Precipitation (continued)						
cyclonic data bases on	-----	-----	112 xxv, xxviii, 40, 160, 169, 173-174, 182	-----	-----	-----
decade-to-decade fluctuations of distribution of estimates for 6000-B.P.	-----	-----	155	-----	-----	-----
GFDL model simulation of evaporation and global average	-----	249	-----	77, 180, 196	-----	74, 156-157
global mean	-----	93	-----	-----	-----	-----
heavy seasonal increase in	-----	-----	xxv, 151, 152	-----	-----	-----
instrumentation for measuring	-----	-----	156	-----	-----	-----
intercepted maps of past patterns	-----	269	-----	-----	26	-----
measurement of over land	-----	-----	152	-----	-----	-----
station location for natural variability of	-----	-----	152, 174	-----	-----	-----
oceanic	-----	-----	153	-----	-----	-----
patterns of poleward shifting of	-----	-----	160	-----	-----	-----
rate of	-----	-----	152, 174	-----	-----	-----
regional shifts in seasonal	-----	93, 104, 141	40, 151-161	-----	-----	-----
simulated changes in simulated geographic distribution of	266	xx, 69, 76, 121, 130-132, 143, 262, 271	-----	-----	154	-----
simulated seasonal variation of	-----	-----	153-159	-----	31, 33, 81, 165	-----
spatial variation of	-----	98	-----	-----	-----	-----
temporal variation of	-----	-----	174	-----	-----	-----
year-to-year variability of	-----	-----	156	-----	81	-----
year-to-year variations in zonally averaged changes in	-----	xxi	-----	-----	-----	-----
Precipitation and evaporation rates	-----	-----	101, 173	-----	-----	-----
Precipitation anomalies:						
Africa	-----	-----	158	-----	-----	-----
Australia	-----	-----	159	-----	-----	-----
India	-----	-----	156-157	-----	-----	-----
United States	-----	-----	154-155	-----	-----	-----
Precipitation data (see also Precipitation, data bases on)	-----	-----	47	-----	-----	-----
Precipitation estimates	-----	-----	-----	-----	162	-----
Precipitation events: characterization of	-----	-----	-----	-----	29, 59, 213	-----
Precipitation intensity: effects on groundwater recharge of	-----	-----	-----	-----	36	-----
Precipitation levels	-----	-----	-----	-----	78	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Precipitation patterns: changes in	-----	-----	165	-----	-----	-----
Precipitation rate and soil moisture	-----	103	-----	-----	-----	-----
Precipitation records (see also Precipitation, data bases on):	-----	-----	-----	-----	-----	-----
global	-----	-----	-----	-----	41	-----
Precipitation timing	-----	-----	-----	-----	31, 165	-----
Precipitation variations:	-----	-----	-----	-----	-----	-----
global	-----	-----	159-160	-----	-----	-----
regional	-----	-----	xxv, 153-159, 174	-----	-----	-----
Africa	-----	-----	157-158	-----	-----	-----
Australia and Indo Pacific	-----	-----	158	-----	-----	-----
China	-----	-----	159	-----	-----	-----
Europe and western Asia	-----	-----	155-156	-----	-----	-----
India	-----	-----	156	-----	-----	-----
Japan	-----	-----	159	-----	-----	-----
Northern Hemisphere	-----	-----	152, 159	-----	-----	-----
South America	-----	-----	159	-----	-----	-----
United States	-----	-----	154-155	-----	-----	-----
Predator avoidance	-----	-----	-----	-----	119	-----
Predator distributions	-----	-----	-----	-----	101, 131, 139	-----
Predator pressures	-----	-----	-----	-----	108, 111	-----
Predators	-----	-----	-----	-----	98, 105, 107, 118, 120, 123, 124, 125, 127, 133, 139, 212	-----
Predictions:	-----	-----	-----	-----	-----	-----
growth and yield	-----	-----	76, 89, 101	-----	-----	-----
vegetation response	-----	-----	40, 47	-----	-----	-----
Pressure:	-----	-----	-----	-----	-----	-----
sea level	75	-----	-----	-----	-----	-----
Pressure data	-----	-----	40-41	-----	-----	-----
Pressure-height data	-----	-----	69	-----	-----	-----
Prey distributions	-----	-----	-----	-----	101, 131, 139	-----
Prey size selectivity	-----	-----	-----	-----	118, 137	-----
Primary productivity (plants)	-----	-----	-----	119, 136, 173, 174	-----	-----
Primary productivity: marine	-----	-----	-----	-----	97, 101, 105, 108, 116, 118, 137, 139, 140	-----
patchiness of	-----	-----	-----	-----	108	-----
Primary succession	188	-----	-----	-----	-----	-----
Principle of Limiting Factors	-----	-----	-----	72	-----	-----
Processes and Resources of the Eastern Bering Sea Shelf	-----	-----	-----	-----	137, 138	-----

Production

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Production:						
below-ground plant	-----	-----	-----	130, 135	-----	-----
flower	-----	-----	-----	130	-----	-----
seed	-----	-----	-----	130, 165	-----	-----
Productivity (business and industry)	243	-----	-----	-----	-----	-----
Productivity (animal breeds)	-----	-----	-----	-----	75, 76, 212	-----
Project Metromex	-----	-----	153	-----	-----	-----
Projections:						
uncertainties in	-----	xxi, 143, 177, 361	-----	-----	-----	-----
Prokaryotic organisms	194	-----	-----	-----	-----	-----
Protein:						
soluble	-----	-----	-----	122	-----	-----
Protein dry matter	-----	-----	-----	69	-----	-----
Protein synthesis:						
heat shock	-----	-----	-----	77	-----	-----
Proterozoic Era	194	-----	-----	-----	-----	-----
Proxy carbon dioxide record	20, 31, 35, 36, 282	-----	-----	-----	-----	-----
Proxy climate record	-----	-----	129	-----	-----	-----
Proxy data:						
definition	-----	18	-----	-----	-----	-----
sources of	-----	64	-----	-----	-----	-----
Public health care:						
changes in	-----	-----	-----	-----	201, 209	-----
Pulp and paper industry	-----	-----	-----	-----	19	-----
Pulse of the planet	42, 51, 55	-----	-----	-----	-----	-----
Pycnocline	-----	-----	-----	-----	102, 114	-----
Pyrgeometer observations	-----	38	-----	-----	-----	-----
Pyrite burial	197	-----	-----	-----	-----	-----
Pyruvate:						
production of	-----	-----	-----	134	-----	-----

Q

Q fever	-----	-----	-----	-----	191	-----
Quantum yield	-----	-----	-----	64-65, 121, 143, 144, 176	-----	-----
Quaternary glacial processes	-----	-----	-----	-----	-----	74
Quasi-biennial oscillation	-----	213	82, 84, 156	-----	-----	-----
Quebec	-----	248	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
R						
Radar: airborne	-----	-----	-----	-----	-----	183, 233, 235
Radar sounding	-----	-----	-----	-----	-----	33, 178, 181, 185
Radiance: effects of atmospheric thermal structure on outgoing	-----	21	-----	-----	-----	-----
Radiation: solar	-----	-----	-----	-----	28, 175	-----
Radiation balance changes in Earth and atmosphere surface	27, 48 241 152, 261 62	-----	-----	-----	-----	-----
Radiation feedback processes	50	-----	-----	-----	-----	-----
Radiation load	-----	-----	-----	56	-----	-----
Radiation models: solar and longwave	36-39	-----	-----	-----	-----	-----
Radiation-transfer calculations	-----	-----	-----	-----	40	-----
Radiative absorption: methods for calculating	33-36	-----	-----	-----	-----	-----
Radiative convective models	13, 49, 70, 85-89, 137, 141, 265, 266, 289-315, 331, 340, 348, 352-353	114	-----	-----	-----	-----
Radiative cooling times	30, 154, 161, 262	-----	-----	-----	-----	-----
Radiative emissions: changes in ground-based monitoring of satellite-based monitoring of spectral distribution of	-----	xviii, 18 xviii, 18 xviii, xix, 19, 26	-----	-----	-----	-----
Radiative energy budget	39-41	-----	-----	-----	-----	-----
Radiative energy transfer	27	-----	-----	-----	-----	-----
Radiative equilibrium temperature	83, 86, 290	-----	-----	-----	-----	-----
Radiative fluxes (see also Longwave fluxes)	xxix, 41	-----	-----	-----	-----	-----
Radiative fluxes: changes in changes in from carbon dioxide seasonal changes in	35, 43 xix, xxiv, 43 43, 246, 265	-----	-----	-----	-----	-----
Radiative forcing	xvii, 28, 42, 43, 264, 326, 327	-----	-----	-----	40, 62	-----
direct surface and tropospheric system	87 36, 43	-----	-----	-----	-----	-----

Radiative heating rates

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Radiative heating rates	-----	30, 154, 161, 262	-----	-----	-----	-----
Radiative relaxation times	-----	160	-----	-----	-----	-----
Radiative transfer	-----	85, 278	-----	-----	-----	-----
Radiative transfer theory	-----	31-32, 49	-----	-----	-----	-----
Radiatively active gases (see Trace gases)	-----	-----	-----	-----	-----	-----
Radio-echo sounding	-----	-----	-----	-----	-----	31, 123, 156, 178, 206
Radioactive compounds	-----	-----	-----	-----	44	-----
Radioactive fallout horizons	-----	-----	-----	-----	-----	183-184
Radiocarbon bomb	xviii, 92-93, 95, 99, 105, 150, 153, 169, 258	-----	-----	-----	-----	15
bomb-produced and natural distribution of natural	179 147, 154 93, 106	-----	-----	-----	-----	-----
Radiological Dating Laboratory, Norwegian Institute of Technology	36	-----	-----	-----	-----	-----
Radiometersonde observations	-----	38	-----	-----	-----	-----
Radiosonde data	-----	-----	41, 67, 69	-----	-----	-----
Radiosonde network	-----	-----	69, 71	-----	-----	-----
Radish	-----	-----	-----	67, 130	-----	-----
Radium-226	91	-----	-----	-----	-----	-----
Radon-222 concentrations of	91 93	-----	-----	-----	-----	-----
Ragweed	-----	-----	-----	-----	192	-----
Rain belt: extratropical	-----	103	-----	-----	-----	-----
Rain forests	-----	-----	24	-----	-----	-----
Rain gauges	-----	-----	153, 160	-----	-----	-----
Rainfall (see also Precipitation)	-----	-----	-----	-----	-----	-----
Rainfall belt	-----	-----	-----	-----	74	-----
Rainfall dependability	-----	-----	-----	-----	81	-----
Rainfall patterns: alteration of	-----	-----	-----	-----	81	-----
Rajasthan Desert	-----	270	-----	-----	-----	-----
Ranges of plants	-----	-----	139	-----	-----	-----
Rate-limiting factors	205	-----	-----	-----	-----	-----
Rayleigh limit	-----	29	-----	-----	-----	-----
Recommended research	-----	-----	-----	-----	-----	5, 10, 33-34, 65-68, 124, 246, 314
Recreation: effects of climate change on	-----	-----	-----	-----	196-197, 200, 212	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Rectification	-----	-----	-----	-----	-----	123
Recurrence horizons	198	-----	-----	-----	-----	-----
Red snow	-----	-----	-----	-----	191	-----
Redfield ratios	56	-----	-----	-----	-----	-----
Reedy Glacier	-----	-----	-----	-----	-----	185
Reflectants	-----	-----	-----	-----	83	-----
Reflectivity (see also Albedo)	-----	61	-----	-----	-----	-----
Reflectivity:						
classes of snow	-----	-----	117	-----	-----	-----
indexes of	-----	-----	117	-----	-----	-----
shifts in snow	-----	-----	111	-----	-----	-----
Reforestation	122, 266	-----	-----	-----	-----	-----
Reforestation legislation	-----	-----	-----	-----	149	-----
Refreezing within the firn	-----	-----	-----	-----	-----	25, 43, 44, 63, 159
Regional climate:						
changes in	-----	-----	76	-----	-----	-----
estimates of	-----	247-249	-----	-----	-----	-----
variations in	-----	99, 239	-----	-----	-----	-----
Relative growth rate (see Growth rate, absolute and relative)	-----	87, 134, 296, 298, 299	-----	-----	-----	-----
Relative humidity (see also Humidity; Water vapor)	-----	315, 330	-----	-----	-----	-----
Relative humidity:						
assumption of constant	-----	95, 138	-----	-----	-----	-----
changes in	-----	136	-----	-----	-----	-----
correlation with cloud cover	-----	136, 298, 313	-----	-----	-----	-----
vertical profile of	-----	-----	-----	-----	-----	-----
Relative sea level	-----	-----	-----	-----	-----	12, 13-15, 59, 86, 101
changes in	-----	-----	94-96, 99, 102, 103, 104, 172	-----	-----	2, 13, 15, 78, 94, 328
rates of change in	-----	-----	94	-----	-----	16, 97
trends in	-----	-----	-----	-----	-----	96, 102
United States	-----	-----	-----	-----	-----	-----
Remineralization	201	-----	-----	-----	-----	-----
Remote sensing (see Satellite remote sensing)	-----	-----	-----	-----	-----	-----
Replacement times, water	93, 106	-----	-----	-----	-----	-----
Report of the Study of Critical Environmental Problems	-----	-----	-----	3	-----	-----
Reproduction	-----	-----	-----	5, 66, 130-132, 168	-----	-----
human	-----	-----	-----	-----	176, 177	-----
Reproductive growth	-----	-----	-----	68, 112	-----	-----
Reproductive potential	-----	-----	-----	xxiii, 131, 209	-----	-----

Reproductive stress

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Reproductive stress on birds and animals	-----	-----	-----	-----	118	-----
Research recommendations	56-58, 78-79, 105-107, 133-134, 141-144, 224-225, 168-171, 203-206, 253, 275-279, 291-301	v, 77-78, 361-362	-----	145, 167, 182, 201, 211	xvi-xviii	-----
agricultural data needed	-----	-----	-----	3, 5, 7, 47, 80, 84, 89, 90, 182	xvii, 88, 90-91	-----
fishery	-----	-----	-----	-----	xvii, 133-136	-----
forestry	-----	-----	-----	-----	xvii, 162	-----
human health	-----	-----	-----	-----	xviii, 197-202	-----
water resource	-----	-----	-----	-----	xvi, 60-62	-----
Reseau Mondial	-----	-----	34	-----	-----	-----
Reserves of natural resources	72-74	-----	-----	-----	-----	-----
Reservoir inflow	-----	-----	-----	-----	50	-----
Reservoir performance simulation	-----	-----	-----	-----	48, 51	-----
Reservoir spill: managed	-----	-----	-----	-----	52	-----
Reservoirs:						
atmospheric	143	-----	-----	-----	-----	-----
carbon (see also Carbon reservoirs)	4, 9, 143-145	-----	-----	-----	-----	-----
fluxes among	9	-----	-----	-----	-----	-----
coupling of	185	-----	-----	-----	-----	-----
number and size of	-----	-----	-----	-----	39	-----
oceanic	143	-----	-----	-----	-----	-----
reliability of water of	-----	-----	-----	-----	30, 35	-----
soil	143	-----	-----	-----	-----	-----
vegetative	143	-----	-----	-----	-----	-----
Resolution:						
satellite (spatial)	-----	-----	-----	-----	-----	37, 234
Resources:						
coal	72-74, 76-77	-----	-----	-----	-----	-----
crude oil	72, 74-75	-----	-----	-----	-----	-----
estimates of	73-74	-----	-----	-----	-----	-----
fossil fuel	224	-----	-----	-----	-----	-----
natural gas	72, 75-77	-----	-----	-----	-----	-----
Respiration	19, 21, 130, 131, 132, 143, 177, 190, 201	-----	-----	3, 125, 173	-----	-----
autotrophic	-----	-----	-----	xxiii, xiv, 173, 182, 207	-----	-----
dark	-----	-----	-----	56, 64, 65, 102, 111, 125, 126, 207, 212	-----	-----
enhanced	55, 297	-----	-----	-----	-----	-----
heterotrophic	119, 132, 143, 146, 177	-----	-----	xxiii, xiv, 173, 182	-----	-----
leaf	-----	-----	-----	148	-----	-----
rate of	-----	-----	-----	56, 76, 77, 82, 136, 137, 143, 176	-----	-----
root	119	-----	-----	-----	-----	-----
soil	-----	-----	-----	24, 55, 70	-----	-----
soil-microorganism	-----	-----	-----	136, 141, 148	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Respiration pulses	54	-----	-----	-----	-----	-----
Respiration rate of plants	-----	-----	-----	-----	75	-----
Respiratory diseases	-----	-----	-----	-----	212	-----
seasonality of weather effects on	-----	-----	-----	-----	181-183	-----
weather effects on	-----	-----	-----	-----	179	-----
Respiratory release of carbon dioxide by the biosphere	53	-----	-----	-----	-----	-----
Response times:						
carbon dioxide uptake	106, 205	-----	-----	-----	-----	-----
ice cap	-----	-----	-----	-----	-----	262
tree	-----	-----	-----	-----	161	-----
vegetative	-----	-----	-----	-----	19	-----
Revelle effect	86, 257, 269	-----	-----	-----	-----	-----
Rheology:						
Earth	-----	-----	-----	-----	-----	34, 94, 328
ice	-----	-----	-----	-----	-----	264
Rhone Glacier	-----	-----	-----	-----	-----	226
Ribulose bisphosphate	118	-----	-----	57, 69, 85, 120, 122, 141	-----	-----
Rice	-----	-----	-----	xxi, 67, 71, 75, 90, 105-109, 111, 126, 237-242	75	-----
Rice paddies	-----	194	-----	-----	-----	-----
Rio Grande	-----	-----	-----	-----	34	-----
River discharges (volumetric)	-----	-----	160	-----	-----	-----
River discharges of plant nutrients	96, 106	-----	-----	-----	-----	-----
River freezeup and breakup records	-----	-----	130, 173	-----	-----	-----
River mouths	-----	-----	-----	-----	114	-----
River transport of organic carbon	95, 184	-----	-----	-----	-----	-----
Riverine productivity	9	-----	-----	-----	-----	-----
Rivers:						
sediment deposits of	296	-----	-----	-----	-----	-----
Robb Glacier	-----	-----	-----	-----	-----	191, 192
Rock cycles	203, 299	-----	-----	-----	-----	-----
Rock masses	184	-----	-----	-----	-----	-----
Rocketsonde data	-----	-----	41, 67	-----	-----	-----
Rocketsonde network	-----	-----	72, 73	-----	-----	-----
Rocky Mountain glaciers	-----	-----	-----	-----	-----	141
Ronne-Filchner Ice Shelf (Filchner-Ronne Ice Shelf)	-----	-----	-----	-----	-----	31, 46, 57, 197, 198, 199, 203-204, 275, 280, 301, 302, 303, 305, 309, 314, 315, 325

Ronne-Filchner Ice Shelf

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ronne-Filchner Ice Shelf:						
ice thickness of	-----	-----	-----	-----	-----	32, 205
surface elevation and	-----	-----	-----	-----	-----	204, 206
bottom profile of	-----	-----	-----	-----	-----	
Roosevelt Island	-----	-----	-----	-----	-----	178, 181
Root branching	-----	-----	-----	46, 70, 177	-----	-----
Root crops	-----	-----	-----	90, 111	-----	-----
Root dry weight gain	-----	-----	-----	67, 83, 90, 160, 207	-----	-----
Root exudation	-----	-----	-----	128, 132-133, 135, 139, 147, 190, 192, 201, 210, 212	-----	-----
Root growth	-----	-----	-----	xxi, 70, 74, 81, 86, 90, 130, 133	-----	-----
Root length	-----	-----	-----	70, 80, 83, 177, 207, 212	-----	-----
Root tissue density	-----	-----	-----	70	-----	-----
Root-to-shoot ratio	-----	-----	-----	67, 89, 90, 103, 104, 105-109, 113, 130, 131, 160, 188, 190, 209, 211, 216, 220, 226, 232, 235, 239, 244, 253, 254, 261, 267	-----	-----
Root zone compartments	-----	-----	-----	14	-----	-----
Roses	-----	-----	-----	71	-----	-----
Ross Barrier	-----	-----	-----	-----	-----	120, 122, 123
Ross Embayment:						
isostatic gravity	-----	-----	-----	-----	-----	188
anomalies in	-----	-----	-----	-----	-----	
submarine topography of	-----	-----	-----	-----	-----	178-179
Ross Ice Shelf	-----	-----	135	-----	-----	28, 46, 53, 55, 57, 119, 122, 174, 175, 178-196, 198, 199, 203, 204, 277, 278, 279, 280, 283-286, 301, 302, 303, 305, 309, 310, 311, 313, 314, 315, 317, 321
advance of	-----	-----	-----	-----	-----	122
basal melting or freezing of	-----	-----	-----	-----	-----	50, 55, 319
dynamics of	-----	-----	-----	-----	-----	193
future thinning of	-----	-----	-----	-----	-----	321-325
geophysical data for	-----	-----	-----	-----	-----	52, 199
melting of	-----	-----	-----	-----	-----	117
present state of	-----	-----	-----	-----	-----	178-181, 199, 319
thickness of	-----	-----	-----	-----	-----	30, 178-181, 317
Ross Ice Shelf Geophysical	-----	-----	-----	-----	-----	178, 317
and Glaciological Survey	-----	-----	-----	-----	-----	

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Ross Ice Shelf Project	-----	-----	-----	-----	-----	210
Ross Ice Shelf Survey	-----	-----	-----	-----	-----	182
Ross Sea	-----	-----	125	-----	-----	5, 20, 21, 48, 117, 118, 119, 178-194, 314 121
continental shelf of	-----	-----	-----	-----	-----	-----
Reservoir performance	-----	-----	-----	-----	48, 51	-----
temperature profile of	-----	-----	-----	-----	-----	118, 119
Rotational response:	-----	-----	-----	-----	-----	98, 99
Earth's (see also Earth, rotation of; Planetary rotation)	-----	-----	-----	-----	-----	-----
Roundwood harvest	-----	-----	-----	-----	147	-----
Row spacing and orientation	-----	-----	-----	82	-----	-----
Rumania	-----	-----	-----	-----	34	-----
Runoff	203	61, 93	116, 151	-----	102, 113, 114, 116, 123, 125, 128, 129, 212	25, 43, 62, 139, 220, 248
annual climatic influences on	-----	-----	-----	197	-----	-----
influences on	-----	-----	-----	-----	29, 60-61	-----
river flow from	-----	-----	160	-----	40, 42	-----
subsurface	-----	-----	-----	-----	27	-----
surface	-----	-----	-----	-----	27	-----
variability of	-----	-----	-----	-----	38, 42	-----
Runoff data	-----	-----	174	-----	-----	-----
Russian Platform	-----	-----	-----	-----	-----	86
Rutford Glacier	-----	-----	-----	-----	-----	204, 315
Rutford Ice Stream	-----	-----	-----	-----	-----	204-205
Rye	-----	-----	-----	-----	75	-----
Rye grass	-----	-----	-----	75, 133, 134, 135, 165	-----	-----

S

Sahara Desert	-----	9, 38, 270	-----	-----	-----	-----
Sahel	-----	-----	157	-----	42	-----
Saint Petersburg	-----	-----	130	-----	-----	-----
Salinity (agricultural)	-----	-----	-----	xxi, xxv, 21, 74, 76, 83, 87, 89, 188, 209, 212	-----	-----
Salinity (oceanic; see also Oceans, salinity of)	10, 83, 85, 90, 95, 105, 168	72, 180	xxiii, 93, 96, 101, 102, 104, 171, 172, 182	-----	100, 102, 103, 114, 116, 120, 125, 128, 130, 131, 132, 134, 213	65, 133, 134, 136
changes in	-----	-----	-----	-----	-----	2, 19, 20, 116-118

Salinity

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Salinity (continued)						
changes in on continental shelves	-----	-----	-----	-----	-----	117-118
measurements of surface	-----	-----	-----	-----	102, 116, 120	116, 117, 136, 202
Salinity (riverine)	-----	-----	-----	-----	62	-----
Salinity of ground and surface waters	-----	-----	-----	-----	45-46, 212, 213	-----
Salinity patterns (oceanic)	-----	-----	-----	-----	101, 113	-----
Salinity problems (agricultural): solutions to	-----	-----	-----	-----	45	-----
Salinity problems (water resources)	-----	-----	-----	-----	59	-----
Salmon	-----	-----	-----	-----	98, 99, 107	-----
Salmonella	-----	-----	-----	-----	190, 191, 193	-----
Salt:						
input to the oceans of transfer of	-----	-----	-----	-----	-----	277
	-----	-----	-----	-----	-----	123, 124
Salt River Basin	-----	-----	-----	-----	46-53	-----
Salt River Project	-----	-----	-----	-----	47	-----
Salt tolerance of plants	-----	-----	-----	76	45, 59	-----
Sandstorms:						
Black Sea	-----	-----	-----	-----	191	-----
Sangamon interglacial period	-----	-----	-----	-----	-----	46
Sanitation	-----	-----	-----	-----	193, 200	-----
Sargasso Sea	90, 167, 180	-----	-----	-----	-----	-----
Saskatchewan	-----	248	-----	-----	-----	-----
Satellite imagery	-----	-----	-----	-----	-----	25, 31, 125, 168, 199, 208, 222, 225-228, 232-237, 241
 Satellite radar	-----	-----	-----	-----	-----	28, 205, 222
Satellite remote sensing	xxiii, 19, 50, 55, 57-58, 84, 92, 125, 127, 132, 133, 135, 201, 280, 293, 295, 298, 299	166, 167, 202, 334	-----	-----	-----	36, 43, 66, 168, 205, 225-228, 232-237, 241, 246
data from	-----	39	xx, xxiv, xxvii, 67, 85, 183, 184	-----	-----	-----
global climatologic irradiance measurements by precipitation	-----	-----	182	-----	-----	-----
radiative-emission	-----	-----	19, 26	-----	-----	-----
snow-and-ice	-----	-----	152	-----	-----	-----
 solar-irradiance	-----	-----	19, 168	-----	-----	-----
Solar Maximum Mission verification of data from	-----	-----	116-117, 122, 124, 126, 129, 134, 137, 173	-----	-----	-----
	-----	-----	46-47, 183	-----	-----	-----
	-----	-----	46	-----	-----	-----
	-----	-----	26	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Saturation equilibrium	87	-----	-----	-----	-----	-----
Saudi Arabia	-----	38, 249	-----	-----	-----	-----
Savannas:						
tropical	122	-----	-----	181	-----	-----
<i>Saxifraga flagellaris</i>	-----	-----	-----	132	-----	-----
Scales for abiotic variability:						
spatial	-----	-----	-----	-----	129	-----
temporal	-----	-----	-----	-----	129	-----
Scandinavia uplift of	-----	-----	-----	-----	-----	85, 141, 223 73
Scanning microwave spectrometer	-----	-----	-----	-----	-----	198
Scanning Multifrequency Microwave Radiometer	-----	-----	124	-----	-----	-----
SCAR Working Group on Glaciology	-----	-----	-----	-----	-----	211
Scattering:						
solar radiation	-----	29, 46	-----	-----	-----	-----
Scenarios:						
construction of definition	-----	243-245 243	-----	-----	-----	-----
Schistosomiasis	-----	-----	-----	-----	194	-----
Schizophrenics' birth months: seasonal variation in	-----	-----	-----	-----	177	-----
Scientific Committee on Problems of the Environment	17, 296	-----	-----	-----	-----	-----
SCOR-UNESCO calibration stations	-----	-----	-----	-----	-----	116
Scoresby Sund	-----	-----	-----	-----	-----	162
Scotia Bay	-----	-----	127	-----	-----	-----
Scotland	-----	-----	-----	-----	-----	85
Scott Polar Research Institute Map Folio	-----	-----	-----	-----	-----	173, 198
Scripps Institution of Oceanography	17, 19, 38, 41	-----	40	-----	-----	-----
Sea floor: uplift of	-----	-----	-----	-----	-----	318
Sea ice	296	8, 61, 90, 96, 138, 140, 152, 186, 262 267, 276	121-129, 138, 139, 166 114, 137	-----	100	124, 241-246
advance and retreat of	-----	-----	-----	-----	-----	-----
annual cycle of growth and	-----	-----	-----	-----	-----	-----
decay of	-----	-----	-----	-----	-----	-----
anomalies of	-----	-----	125-126, 127	-----	-----	-----
Antarctic	-----	-----	111, 126	-----	-----	-----
Arctic	-----	-----	111, 124	-----	-----	-----
breakup of	-----	18	-----	-----	-----	36-39, 41, 50
changes in	-----	-----	-----	-----	-----	-----
concentration of	-----	-----	122, 124	-----	-----	-----
cooling of surface waters by	-----	-----	112	-----	-----	-----
decay of	-----	-----	-----	-----	-----	122

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Sea ice (continued)						
drift and divergence of	-----	-----	125	-----	-----	66, 122
drift of	-----	-----	-----	-----	-----	-----
duration of	-----	-----	127	-----	-----	-----
effects of climate on	-----	-----	128	-----	-----	-----
effects of solar radiation on	-----	-----	128	-----	-----	-----
effects on climate of	-----	-----	124, 126, 127	-----	-----	-----
formation and temperature	-----	-----	124	-----	-----	-----
indices of	-----	-----	-----	-----	-----	-----
formation of	-----	-----	-----	-----	-----	116, 125
variations in	-----	-----	-----	-----	-----	20, 121
geographic distribution of	-----	-----	122	-----	-----	-----
historical records of	-----	-----	122	-----	-----	-----
location of edge of	-----	-----	125	-----	-----	-----
long-term monitoring of	-----	-----	-----	-----	-----	39
melting of	190	-----	-----	-----	-----	-----
multiyear fraction of	-----	-----	124	-----	-----	-----
seasonal dependence of	-----	-----	173	-----	-----	-----
seasonal trends in	-----	72, 266	121, 125	-----	-----	-----
surface heat balance of	-----	-----	125	-----	-----	-----
thermal inertia feedback of	-----	-----	113	-----	-----	-----
thermodynamic model of	-----	-----	114	-----	-----	-----
growth of	-----	-----	-----	-----	-----	-----
thermodynamic processes of	-----	-----	115	-----	-----	-----
thickness of	-----	-----	127	-----	-----	66, 122, 241
time scale of	-----	162	-----	-----	-----	-----
Sea ice charts:						
weekly	-----	-----	122-123	-----	-----	-----
Sea ice concentration	-----	-----	-----	-----	-----	47
Sea ice cover	57	-----	-----	-----	102, 105, 111,	232
Sea ice extent	-----	89, 144, 151, 267, 271	xxiii, 112, 124, 127, 137, 173	-----	101, 102, 111, 114, 126, 129, 133, 139, 140, 213	37, 47, 207, 241, 245
anomalies in	-----	-----	126, 172	-----	-----	-----
historical observations of	-----	-----	-----	-----	-----	241
monitoring with satellites of	-----	-----	116	-----	-----	-----
simulation of	-----	116	-----	-----	-----	-----
summer temperatures and	-----	-----	124	-----	-----	-----
trends in	-----	-----	-----	-----	-----	39, 243
winter	-----	-----	-----	-----	-----	246, 326
Sea ice floes	-----	-----	124	-----	-----	-----
Sea ice zone:						
circumglobal marginal	-----	-----	121	-----	-----	-----
Sea floor spreading	31	-----	-----	-----	-----	-----
Sea level	-----	62	6, 93, 102, 166, 171	35	-----	ix, 9, 46, 89, 104-115, 145-154, 178, 258-266
changes of	3, 34, 97, 192, 197, 198	-----	xxii, xxiv, 94-95, 133, 135, 136-137, 139, 172, 173, 174, 175	-----	v, 83	12-39, 45, 60, 74, 75, 142, 151, 152, 155-171, 176, 205
effects of small ice caps on	-----	-----	-----	-----	-----	60
eustatic rise of	-----	-----	-----	-----	-----	23, 73
global	-----	-----	95, 104, 112	-----	-----	-----
ice-discharge-induced rise of	-----	-----	-----	-----	-----	64, 256, 301

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Sea level (continued)						
mean	-----	-----	94-96	-----	-----	-----
measurements of	-----	-----	94, 172	-----	-----	12-14, 73-90, 92
methods for measuring	-----	-----	94	-----	-----	-----
predictions of	-----	-----	-----	-----	-----	58, 326, 327
projections of rise of	-----	-----	-----	-----	-----	6, 45, 264, 317-328
rate of rise of	-----	-----	-----	-----	-----	44, 59, 79, 86, 95, 262, 263
relative (see also Relative sea level):	-----	-----	-----	-----	-----	40, 73, 98, 220
response of to climate change	-----	-----	-----	-----	-----	-----
rise of	-----	-----	-----	-----	-----	1, 2, 7, 28, 31, 39, 40, 41, 43, 44, 54, 55, 56, 64, 73, 75, 83, 89, 92, 114, 139, 144, 152, 188, 198, 206, 237, 241, 243, 248, 252, 253, 281, 309, 310-311, 312, 314, 316
tectonic effects on trends in	-----	-----	-----	-----	-----	73 93, 110
Sea level data	-----	-----	-----	-----	-----	76, 77, 81, 84, 105
biases in	-----	-----	-----	-----	-----	13
Sea level signatures	-----	-----	-----	-----	-----	65, 74, 83
Sea level stations	-----	-----	94, 104	-----	-----	65
Sea level variability	-----	-----	-----	-----	-----	104, 232, 257-266
Sea level variance at the coast	-----	-----	-----	-----	-----	60, 76-80, 111
Sea lions	-----	-----	-----	-----	107	-----
Sea of Okhotsk	-----	-----	121, 126	-----	-----	-----
Sea surface freezing	-----	-----	-----	-----	-----	118
Sea surface temperatures	48-49, 57, 95, 131, 167, 168	77, 96-104, 131, 262, 323, 355, 35675-76, 93, 96, 104, 182	xxviii, 39, 57, 93, 96, 104, 182	-----	102, 108, 119, 122	-----
anomalies in	47-50, 52	-----	-----	-----	-----	-----
changes in	-----	-----	64, 67	-----	-----	-----
comparison of with marine air temperatures	-----	-----	75, 99	-----	-----	-----
estimates of	-----	247, 249	-----	-----	-----	-----
fisheries yield and	-----	-----	-----	-----	108	-----
induced oscillations in	167	-----	-----	-----	-----	-----
latitudinal variation of	-----	90, 98	-----	-----	-----	-----
measurement methods of	-----	-----	xx, 62, 97, 99	-----	-----	-----
projected	-----	-----	-----	-----	122	-----
records of	-----	-----	xix	-----	-----	-----
seasonal mean	-----	-----	61	-----	-----	-----
Sea surface warming	33, 191	-----	-----	-----	-----	-----
Sea water:						
freshening of	-----	-----	-----	-----	-----	116, 118, 129
residence time beneath the ice of	-----	-----	-----	-----	-----	123

Seagoing studies

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Seagoing studies	-----	-----	-----	-----	137	-----
Seals	-----	-----	-----	-----	107, 118, 123	-----
SEASAT	-----	-----	-----	-----	-----	235, 237
Seasonal exchange curves	166	-----	-----	-----	-----	-----
Seasonal rhythms in humans	-----	-----	-----	-----	175-177, 183-184	-----
Seasonal vegetation	191	-----	-----	-----	-----	-----
Seawater standards	21	-----	-----	-----	-----	-----
Secondary effects on plant growth	-----	-----	-----	5, 7	-----	-----
Sediment cores	xvi, 28, 31, 34, 56	-----	-----	-----	-----	-----
Sediment layers in lakes	-----	18	-----	-----	-----	-----
Sediment records	-----	-----	-----	-----	-----	282
Sediment yields	-----	-----	-----	-----	44	-----
Sedimentary rocks	181, 195	-----	-----	-----	-----	-----
Sedimentation patterns of river	-----	-----	-----	-----	40, 134, 136 125 43-45, 59, 62, 212, 213, 215, 218	-----
Sedimentation rate	-----	-----	-----	-----	-----	74
Sediments	xix, xxiii, 87, 96, 181, 184, 191, 194, 203, 271, 296, 299	-----	-----	-----	-----	-----
alluvial	126, 257	-----	-----	-----	-----	-----
coastal ocean	95, 97, 106, 191, 198, 253	-----	-----	-----	-----	-----
deep ocean	55, 95	-----	-----	-----	-----	-----
estuarine	95, 106, 191	-----	-----	-----	-----	-----
lake	-----	-----	-----	-----	-----	46
Seed dispersal	-----	-----	-----	139-140, 210	-----	-----
Seed distribution: natural limitations on	-----	-----	-----	-----	221	-----
Seed nitrogen concentration	-----	-----	-----	74	-----	-----
Seed quantity	-----	-----	-----	71, 160, 168, 188	-----	-----
Seed set: timing of	-----	-----	-----	xxiii, 160	-----	-----
Seed size	-----	-----	-----	129, 130, 188	-----	-----
Seed source availability (trees)	-----	-----	-----	-----	151, 152, 157	-----
Seed weight	-----	-----	-----	71, 129, 160, 258, 259, 270, 271	-----	-----
Seed yield	-----	-----	-----	130, 167, 168, 175, 241, 271	-----	-----
Seedling survival	-----	-----	-----	-----	149, 155, 212, 213	-----
Seedlings	-----	-----	-----	127	-----	-----
growth of	-----	-----	-----	129, 141	-----	-----
growth patterns of	-----	-----	-----	55, 141, 160	-----	-----
Seeds	-----	-----	-----	67	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Self shading (plants)	-----	-----	-----	161	-----	-----
Sensible and latent heat transfer	-----	93, 261, 262	-----	-----	-----	-----
Sensible heat flux	-----	285, 325, 331, 332	-----	-----	-----	43, 255
Sensitivity analysis	225, 274	340, 344, 347-350	-----	36, 84, 213	-----	-----
Sequence of environmental conditions	-----	-----	-----	68	-----	-----
Sewage	96	-----	-----	-----	-----	-----
Shading (forest): increased	-----	-----	-----	-----	151	-----
Shale oil	258	-----	-----	-----	-----	-----
Sheep	-----	-----	-----	-----	76	-----
Shelf-slope exchanges dynamics of	-----	-----	-----	-----	-----	50 124
Shelfwater: residence time of	-----	-----	-----	-----	-----	121, 122, 125
Shellfish	-----	-----	-----	-----	99, 118, 128	-----
Shelter	-----	-----	-----	-----	xviii	-----
design of	-----	-----	-----	-----	200, 216	-----
loss of	-----	-----	-----	-----	189	-----
materials for	-----	-----	-----	-----	173	-----
types of	-----	-----	-----	-----	201-202	-----
Shelter change: climate-induced	-----	-----	-----	-----	196	-----
Ships' observations: historical archives of sea ice	-----	-----	104	-----	-----	-----
-----	-----	-----	173	-----	-----	-----
Shoreline: conflicting uses of orientation of	-----	-----	-----	-----	99	-----
-----	-----	-----	-----	-----	113	-----
Short-term experiments: applicability to trees of	-----	-----	-----	-----	161	-----
Shortwave radiation (see Solar radiation)	-----	-----	-----	-----	-----	-----
Showy crotalaria	158	-----	-----	-----	-----	-----
Shrimp (see also Pink shrimp)	-----	-----	-----	-----	98, 106-107, 112, 119, 120-121, 123-124, 129, 140	-----
Shrubs	-----	-----	-----	121	-----	-----
Siberia	-----	-----	121, 131, 132	-----	-----	-----
Sicklepod	-----	-----	-----	158, 159, 162	-----	-----
Sidewelling	156	-----	-----	-----	-----	-----
Signal-to-noise ratio	-----	152, 244	7, 80-81, 127, 179	-----	-----	86
definition	-----	14	-----	-----	-----	-----
Silicate fluxes	195	-----	-----	-----	-----	-----
Silicates	90, 168, 203	-----	-----	-----	-----	-----
Silicon cycle	293	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Silver maple	-----	-----	-----	158	-----	-----
Single-leaf responses	-----	-----	-----	65	-----	-----
Sink-to-source ratio	-----	-----	-----	57, 58	-----	-----
Siple Station, Antarctica	36-37, 252	-----	-----	-----	-----	-----
Sitka, Alaska	-----	-----	36	-----	-----	-----
Sky coloration records	-----	-----	42	-----	-----	-----
Sliding law	-----	-----	-----	-----	-----	293, 294, 297
Small ice caps: effects on sea level of	-----	-----	-----	-----	-----	60
Smithsonian Institution	-----	166	-----	-----	-----	-----
Smithsonian plates	30, 36, 56	-----	-----	-----	-----	-----
Snail breeding (see also Schistosomiasis)	-----	-----	-----	-----	194	-----
Snow (see also Precipitation; Snow and ice; Snow cover; Snowfall): accumulation of accumulation rates of redistribution of by wind	-----	103	-----	-----	74	-----
Snow albedo feedback definition	-----	107	-----	-----	-----	-----
Snow and ice	-----	61	-----	-----	-----	-----
albedo feedbacks of	-----	-----	114, 115	-----	-----	-----
area of	-----	-----	112	-----	-----	-----
changes in	-----	296	114	-----	-----	-----
components of	-----	-----	-----	-----	-----	242
cooling effects of	-----	-----	112, 119	-----	-----	-----
data coverage of	-----	-----	173	-----	-----	-----
effects of climate on	-----	-----	137	-----	-----	-----
effects on the atmospheric circulation of	-----	-----	112, 120	-----	-----	-----
extent of	-----	-----	114, 115, 119, 173, 181	-----	-----	-----
feedback effects of	-----	-----	xxiii, 113	-----	-----	-----
insulating properties of	-----	61	112, 116, 118, 133	-----	-----	-----
standardized data on	-----	-----	111	-----	-----	-----
thermal capacity of	-----	8	-----	-----	-----	-----
thermal conductivity of	-----	61	-----	-----	-----	-----
thickness of	-----	-----	172	-----	-----	-----
time scale of	-----	162	-----	-----	-----	-----
Snow and ice cover: long-term global data sets of	-----	-----	139, 182	-----	-----	-----
Snow and ice line	-----	-----	113	-----	-----	-----
<i>Snow and Ice Research, an Assessment</i>	-----	-----	-----	-----	-----	10
Snow cover (see also Snow and ice cover)	-----	8, 61, 155, 262	xxiv, 111, 115-121, 138, 139, 182	-----	102	36-39, 232, 241-246
advance and retreat of	-----	271, 276	-----	-----	-----	-----
changes in	-----	-----	-----	-----	-----	37, 38
effects on air temperature of	-----	-----	121	-----	-----	-----
effects on monsoon rainfall of	-----	-----	121	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Snow cover (continued)						
extent of	-----	-----	114, 120, 139, 172, 173	-----	-----	-----
fluctuations of	-----	-----	119	-----	-----	-----
interactions of climate with	-----	-----	118	-----	-----	-----
long-term monitoring of	-----	-----	-----	-----	-----	39, 246
mapping of	-----	-----	117	-----	-----	-----
observations of	-----	-----	116-117	-----	-----	-----
records of	-----	-----	118	-----	-----	-----
regional variations in	-----	-----	120	-----	-----	-----
satellite monitoring of	-----	-----	116	-----	-----	-----
seasonal dependence of	-----	-----	173	-----	-----	-----
spatio-temporal	-----	-----	117	-----	-----	-----
variability in	-----	-----	-----	-----	-----	-----
trends in	-----	-----	-----	-----	-----	244
variability of	-----	-----	-----	-----	-----	241, 243
world distribution of	-----	-----	119	-----	-----	-----
Snow depth:						
winter	-----	-----	117	-----	-----	-----
Snow gum	-----	-----	-----	59	-----	-----
Snow lines:						
elevation of	-----	-----	-----	-----	29	-----
Snow melt	-----	103, 133	-----	-----	27, 28, 42, 46, 47, 74, 212	-----
determinants of	-----	-----	-----	-----	29	-----
influences on	-----	-----	118-119	-----	-----	-----
Snow pits	-----	-----	-----	-----	-----	139, 156
Snow transition zone	-----	-----	119	-----	-----	-----
Snowfall (see also	-----	271	-----	-----	9, 31, 36, 58, 150, 187, 197, 241, 246	-----
Precipitation)	-----	-----	-----	-----	-----	-----
effect of increasing	-----	-----	120, 173	-----	-----	-----
temperatures on	-----	-----	-----	-----	-----	-----
measurement of	-----	-----	40, 117	-----	-----	-----
temperatures during	-----	-----	-----	-----	-----	150
Snowmass	-----	-----	-----	-----	25	-----
Snowpack:						
radiation penetration of	-----	-----	119	-----	-----	-----
Societal activities:						
impacts on	11, 278	-----	165	-----	-----	-----
influences of	-----	-----	171, 183, 184, 185	-----	-----	-----
Societal adaptation to the	-----	3	-----	-----	-----	-----
climate system	-----	-----	-----	-----	-----	-----
Societal reactions	78	-----	-----	-----	-----	-----
Societal stability:						
effects of food supply on	-----	-----	-----	-----	71	-----
Societe Royale de Medicine	-----	-----	31-32	-----	-----	-----
de France	-----	-----	-----	-----	-----	-----
Softwoods	-----	-----	-----	-----	147	-----
northern:	-----	-----	-----	-----	-----	-----
disappearance of	-----	-----	-----	-----	161	-----
Soil biota	-----	-----	-----	-----	163	-----
Soil bulk density	-----	-----	-----	81	-----	-----

Soil carbon dioxide flux

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Soil carbon dioxide flux	-----	-----	-----	142	-----	-----
Soil carbon reservoir	6, 53, 197, 271, 294	-----	-----	-----	-----	-----
Soil carbon sequestering	-----	-----	-----	xviii, xxii, xxiii, 3, 7, 35, 119, 135-136, 138, 142, 145, 148, 212	-----	-----
Soil compaction	-----	-----	-----	-----	28	-----
Soil Conservation Service	-----	-----	117	-----	83	-----
Soil decomposition drainage and temperature effects on	-----	-----	-----	135-136, 137 137	-----	-----
Soil erodibility characteristics	-----	-----	-----	-----	xvii, 79	-----
Soil erosion	96, 257, 258	-----	-----	xxv, 77, 193, 200, 201	-----	-----
Soil exhaustion	-----	-----	-----	-----	72	-----
Soil genesis	199, 202, 263, 299	-----	-----	-----	-----	-----
Soil horizons	181, 195	-----	-----	81	80	-----
Soil hydraulic conductivity	-----	-----	-----	81, 113	-----	-----
Soil infiltration capacity	-----	-----	-----	-----	28	-----
Soil microorganisms: respiration of	-----	-----	-----	136, 141, 148	-----	-----
Soil moisture	-----	62, 73, 103, 141, 262	-----	-----	25, 151, 165	-----
annual mean carryover of changes in geographic distribution of changes of	-----	104	-----	-----	46	-----
	-----	94, 103, 133, 134, 141	-----	-----	-----	-----
	-----	48, 93, 94, 95, 99, 102, 103, 105, 134	-----	-----	-----	-----
Soil moisture depletion studies	-----	-----	-----	21, 194	-----	-----
Soil nitrogen levels	-----	-----	-----	135, 176, 190	-----	-----
Soil nutrients	-----	-----	-----	xviii, xxii, 13, 190	-----	-----
Soil organic matter	115, 118, 122, 126, 143, 294	-----	-----	81, 135, 190, 200, 201	-----	-----
Soil particle size analyses	-----	-----	-----	81	-----	-----
Soil permeability	-----	-----	-----	-----	45	-----
Soil Plant Atmosphere Model	-----	-----	-----	77-78	-----	-----
Soil Plant Atmosphere Research Unit (SPAR)	-----	-----	-----	19	-----	-----
Soil processes	-----	-----	-----	132	-----	-----
Soil productivity	-----	-----	-----	-----	80-81	-----
Soil profiles	117-118, 181	-----	-----	-----	-----	-----
Soil properties	-----	-----	-----	193	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Soil resources:						
adequacy of	-----	-----	-----	-----	78	-----
Soil structure	-----	-----	-----	13	41, 59	-----
modification of	-----	-----	-----	-----	31	-----
Soil sugar levels	-----	-----	-----	135	-----	-----
Soil temperature	-----	-----	-----	-----	75, 151, 155	-----
Soil thermal conductivity	-----	-----	-----	81	-----	-----
Soil types	-----	-----	-----	47	80	-----
Soil water (see also Soil moisture)	-----	132-134	-----	xxi, 6, 74, 77, 83, 86, 87, 139, 148	-----	-----
Soil-water balance	-----	-----	-----	-----	75	-----
Soil-water content	-----	-----	-----	xviii, 13, 163	-----	-----
Soil-water depletion studies	-----	-----	-----	195	-----	-----
Soil-water evaporation	-----	-----	-----	66, 77, 193	-----	-----
Soil-water release curve	-----	-----	-----	81	-----	-----
Soil-water reserve	-----	-----	-----	-----	81	-----
Soils	xix, xxiii, 115, 117-118, 156, 163, 179, 187, 200, 201, 291, 297, 300	-----	-----	-----	80	-----
anaerobic	-----	-----	-----	138	-----	-----
arid	118	-----	-----	-----	-----	-----
carbon accumulation by	122	-----	-----	-----	-----	-----
grassland	122	-----	-----	-----	-----	-----
plant-available water in	-----	-----	-----	-----	81	-----
storage of carbon by	117, 199, 277	-----	-----	-----	-----	-----
thermal conductivity of	-----	62	-----	-----	-----	-----
water-logging of	-----	-----	-----	-----	32, 83	-----
wetland	119, 181, 253	-----	-----	-----	-----	-----
Solar absorption spectra	36	-----	-----	-----	-----	-----
Solar activity	91, 278	222	-----	-----	13	-----
Solar climate relationships	-----	-----	47	-----	-----	-----
Solar constant (see also Solar irradiance)	-----	95, 113, 134, 165, 166, 193, 201-202, 215, 224, 225, 309, 312	-----	-----	-----	-----
Solar cycle:						
annual	-----	104	-----	-----	-----	-----
seasonal	-----	326	-----	-----	-----	-----
Solar diameter	-----	166, 202	47, 169	-----	-----	-----
Solar disk:						
emission regions of the	-----	203	-----	-----	-----	-----
Solar eclipses	-----	221	-----	-----	-----	-----
Solar flux	-----	xviii, 67, 153, 267, 325, 328, 331	-----	-----	-----	-----
variations in	-----	xxii, 184, 324	-----	-----	-----	-----
Solar flux components	-----	31	-----	-----	-----	-----

Solar forcing

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Solar forcing	-----	165-167, 309	-----	-----	-----	-----
Solar forcing function	-----	-----	-----	77	-----	-----
Solar insolation	-----	5, 21	-----	-----	-----	-----
Solar irradiance (see also Solar constant; Solar radiation)	-----	-----	xix, xxvii, 45-47, 83, 118, 166, 171, 183, 184, 185	-----	-----	-----
Solar irradiance:						
actinometric measurements of	-----	-----	45	-----	-----	-----
changes in	-----	-----	169	-----	-----	-----
climate sensitivity to:						
changes in	-----	163	-----	-----	-----	-----
local variability of	-----	-----	167	-----	-----	-----
measurements of	-----	202	-----	-----	-----	-----
multidecade cycles in	-----	-----	184	-----	-----	-----
reduction of by volcanic	-----	-----	45, 165	-----	-----	-----
eruptions	-----	-----	-----	-----	-----	-----
satellite measurements of	-----	-----	46, 47, 169	-----	-----	-----
sensitivity of model	-----	163, 215, 344	-----	-----	-----	-----
climates to						
variation of	-----	xviii, 163, 171, 201, 267, 278, 279	-----	-----	-----	-----
Solar magnetic cycle	191	-----	-----	-----	-----	-----
Solar Maximum Mission	-----	166, 167, 202	46	-----	-----	-----
Solar power	78, 79, 179, 258, 259	-----	-----	-----	-----	-----
Solar radiation (see also Solar irradiance)	xv, 296	5, 6, 7, 29, 31, 32, 113, 167, 193, 325	4, 111, 134, 165	3, 18, 76, 80, 81, 173	-----	-----
absorption of	-----	29, 40, 43, 113	-----	-----	-----	-----
carbon dioxide's	-----	91, 270	-----	-----	-----	-----
Earth's surface's	-----	271	-----	-----	-----	-----
role of water vapor in	-----	31	-----	-----	-----	-----
backscattering of by aerosols	-----	47, 167	-----	-----	-----	-----
balance of	-----	19	-----	-----	-----	-----
budget of	-----	40, 199	-----	-----	-----	-----
emission of by carbon dioxide	-----	91, 270	-----	-----	-----	-----
fluxes of	-----	285	-----	-----	-----	-----
heating rates of	-----	31, 46	-----	-----	-----	-----
incoming	-----	27, 65, 270	-----	-----	-----	-----
net incoming flux of	-----	-----	167	-----	-----	-----
parameterization of	-----	68	-----	-----	-----	-----
values of	-----	252	-----	-----	-----	-----
variations of	-----	59, 64, 193, 265, 268	-----	-----	-----	-----
Solar rotation	-----	202	-----	-----	-----	-----
Solar UV flux: variation of	-----	201	-----	-----	-----	-----
Solar variability effects of	-----	-----	46, 47, 175, 184	-----	-----	-----
Solar variations: effects of	-----	59, 265, 268	-----	-----	-----	-----
Solar zenith angle	-----	44, 46, 47, 48, 86, 114, 290, 291, 306	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level	
Soot	-----	45, 200	-----	-----	-----	-----	
Sorghum	-----	-----	-----	xxi, 6, 59, 71, 90, 103, 105-109, 111, 112, 133, 161, 162, 192, 243-244	75, 76, 77, 79	-----	
Sounding (see Radio echo sounding; Radar sounding)							
Source-to-sink ratio	58, 59	-----	-----	-----	-----	-----	
Sources:							
historical or documentary	129	-----	-----	-----	-----	-----	
South Africa	-----	-----	-----	-----	127	-----	
South America	71, 131	129, 132	159, 160	-----	42	-----	
South Cascade Glacier	-----	-----	-----	-----	-----	35, 223	
South Georgia	-----	-----	-----	-----	-----	197, 207	
South Pole	18, 37, 43, 45, 47, 48, 53, 55	-----	-----	180	-----	-----	
Southern Hemisphere	-----	162, 218, 278	-----	-----	127	-----	
average temperature data for	-----	-----	59-63	-----	-----	-----	
ice core record for	-----	-----	44	-----	-----	-----	
incompleteness of	-----	-----	39-40, 58, 59-63,	-----	-----	-----	
temperature record for	-----	-----	67, 171, 182, 183	-----	-----	-----	
lack of oceanic data for	-----	-----	94, 104, 171, 182	-----	-----	-----	
lag in response behind the	-----	175	-----	-----	-----	-----	
Northern Hemisphere of	-----	-----	111-112	-----	-----	-----	
snow cover of	-----	-----	69	-----	-----	-----	
tropospheric temperatures for	-----	-----	-----	-----	-----	-----	
Southern Ocean	-----	-----	121, 127, 129	-----	-----	62, 116-125	
circulation of the	157	-----	-----	-----	-----	5, 20-23, 66	
total icebergs in the	-----	-----	-----	-----	-----	33, 213	
warming of the	-----	-----	-----	-----	-----	48, 50	
Southern Oscillation	132	5, 279	84, 156, 158, 174	-----	-----	-----	
global scale of	-----	-----	156	-----	-----	-----	
Southern Oscillation Index	48, 49	-----	72	-----	-----	80	
Soybeans	-----	-----	-----	xvii, xxi, 13, 18, 19, 57, 58, 59, 62, 67, 68, 69, 70, 71, 72, 74, 78, 79, 103, 105-109, 111, 112, 113, 114, 157, 158, 159, 162, 163, 174, 175, 178, 179, 189, 192, 195, 210, 245-260	72, 75, 76, 77	-----	-----
SOYMOD	-----	-----	-----	38, 45	-----	-----	
Space Shuttle	-----	-----	-----	-----	-----	36, 235	
Spawner/recruit hypothesis	-----	-----	-----	-----	110	-----	
Spawning:							
intertidal	-----	-----	-----	-----	128	-----	
Spawning grounds	-----	-----	-----	-----	44, 119, 123, 140	-----	

Spawning population

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Spawning population: adult	-----	-----	-----	-----	109	-----
Spawning times and prey availability	-----	-----	-----	-----	119	-----
Species adaptation	-----	-----	-----	45	-----	-----
Species competition	-----	-----	-----	ix, 45, 133, 140, 148, 160, 167, 192, 209, 211	-----	-----
Species composition of marine communities	-----	-----	-----	-----	137	-----
Species composition of plant communities	-----	-----	-----	xxiii, 133, 134, 139, 148, 167, 182	28, 36	-----
Species distribution	-----	-----	-----	35, 162, 209	-----	-----
Species dominance	-----	-----	-----	160	-----	-----
Species interactions	-----	-----	-----	35, 45	-----	-----
Species replacements of fish	-----	-----	-----	-----	119	-----
Species replacements of trees	-----	-----	-----	-----	161	-----
Specific leaf area	-----	-----	-----	68	-----	-----
Specific volume (glacial): trends in	-----	-----	-----	-----	-----	110
Spectrographic plates	21, 56	-----	-----	-----	-----	-----
Spectroscopic data	30, 36	-----	-----	-----	-----	-----
Spectroscopic measurements	-----	262	-----	-----	-----	-----
Spirulina	-----	-----	-----	165	-----	-----
Spodosols	-----	-----	-----	-----	80	-----
Sporer solar activity minima	-----	-----	46	-----	-----	-----
SPOT imagery	-----	-----	-----	-----	-----	226
SPOT satellite	-----	-----	-----	-----	-----	36
Sprinkler systems	-----	-----	-----	-----	83	-----
Stable Carbon Isotope Measurement Program	45	-----	-----	-----	-----	-----
Stagnant weather conditions (see Air pollution)	-----	-----	-----	-----	-----	-----
Stake measurements of glaciers	-----	-----	-----	-----	-----	147
Stancomb-Wills Ice Stream	-----	-----	-----	-----	-----	200
Standard reference materials	17	-----	-----	-----	-----	-----
Standards	41	-----	-----	-----	-----	-----
Starch accumulation	-----	-----	-----	57, 58, 68, 74, 83, 85, 120, 207	-----	-----
Starch density	-----	-----	-----	69	-----	-----
State Hydrological Institute, Leningrad	-----	-----	39	-----	-----	-----
Station Pappa	49	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Statistical analyses:						
problems with	-----	-----	7	-----	-----	-----
Statistical dynamical models	-----	70	-----	-----	-----	-----
Steady-state paradigm	130, 133	-----	-----	-----	-----	-----
Stem dry weight gain	-----	-----	-----	67, 83, 160	-----	-----
Stem growth	-----	-----	-----	70, 86, 129-130	-----	-----
Stem tissue density	-----	-----	-----	70	-----	-----
Step-function forcing	-----	15, 172, 173, 184	-----	-----	-----	-----
Steric changes:						
definition	-----	-----	-----	-----	-----	12
Steric depth (see Steric height)	-----	-----	-----	-----	-----	-----
Steric effect	-----	96	-----	-----	-----	102
Steric height (depth)	-----	-----	-----	-----	-----	105
definition	-----	-----	-----	-----	-----	106
profiles of variations in yearly anomalies	-----	-----	-----	-----	-----	17, 108
-----	-----	-----	-----	-----	-----	17, 104, 114, 115
-----	-----	-----	-----	-----	-----	107
Stockholm Group	152	-----	-----	-----	-----	-----
Stolons:						
mean dry weight of	-----	-----	-----	132	-----	-----
Stomata	-----	-----	-----	xxi, 55, 74, 76, 81, 112, 188, 193	19, 28	-----
definition	-----	-----	-----	56	-----	-----
Stomatal apertures	-----	-----	-----	5, 47, 56, 157, 207	-----	-----
Stomatal conductance	-----	-----	-----	ix, xxv, 63, 64, 112, 125, 126, 129, 159, 169, 194, 201, 207	-----	-----
Stomatal diffusion resistance	-----	-----	-----	25, 59	-----	-----
Stomatal resistance	-----	-----	-----	-----	35	-----
Stomatal responses	-----	-----	-----	61, 141, 176	-----	-----
Storage root volume	-----	-----	-----	83	-----	-----
Storis drift	-----	122	-----	-----	-----	-----
Storm tracks:						
North Pacific shifts in	-----	-----	-----	-----	114, 116	-----
-----	-----	-----	-----	-----	101, 103, 125	-----
Storminess	-----	-----	-----	-----	100, 114, 129, 210, 215	-----
Storms	-----	-----	-----	-----	xv, 27, 29, 42, 165, 189, 214, 215	-----
modeling of	-----	-----	-----	-----	-----	47
Strain rates:						
glacial-surface ice	-----	-----	-----	-----	-----	168
-----	-----	-----	-----	-----	-----	150, 327
Stratigraphic carbon	195	-----	-----	-----	-----	-----
Stratigraphic column	xvi, 177, 179, 300	-----	-----	-----	-----	-----

Stratigraphy

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Stratigraphy	-----	-----	-----	-----	-----	31
Stratosphere aerosols in	-----	29 45, 167-169, 182, 193, 222	----- 42, 45, 82, 83, 165, 170, 183, 184, 185	-----	-----	-----
carbon dioxide-induced cooling of	-----	-----	20, 166, 171	-----	-----	-----
change in temperature of	-----	87, 91, 100, 125, 140, 267, 286	-----	-----	-----	-----
chemistry of	-----	223	-----	-----	-----	-----
definition	-----	6	-----	-----	-----	-----
heating of	50	-----	-----	-----	-----	-----
longwave emission from	-----	270	-----	-----	-----	-----
radiative budget of	-----	29-30, 40	-----	-----	-----	-----
stratification in	-----	86, 291	-----	-----	-----	-----
temperature distribution of	-----	86, 220, 290	-----	-----	-----	-----
temperatures of	-----	-----	67, 72-74, 168	-----	-----	-----
comparison with	-----	-----	81-82, 175	-----	-----	-----
tropospheric temperatures of	-----	-----	-----	-----	-----	-----
Stratosphere-troposphere exchange mechanisms	-----	222, 225	-----	-----	-----	-----
Stream channel degradation	-----	-----	-----	-----	43	-----
Streamflow	-----	-----	-----	197, 198, 200, 209	29, 36, 49, 60-61, 215	-----
climate-induced changes in	-----	-----	-----	-----	48	-----
forecasting of	-----	-----	-----	-----	52	-----
Stress tolerance in plants	-----	-----	-----	-----	76	-----
Stress:	-----	-----	-----	-----	-----	-----
effects of glacial	-----	-----	-----	-----	-----	52
grounding on	-----	-----	-----	-----	-----	-----
Stresses in ice:	-----	-----	-----	-----	-----	-----
shear	-----	-----	-----	-----	-----	188, 318, 327
basal	-----	-----	-----	-----	-----	226, 295-296, 298
Strip cropping	-----	-----	-----	-----	80	-----
Striped bass	-----	-----	-----	-----	128	-----
Stroke	-----	-----	-----	-----	178, 179, 181	-----
Study areas:	-----	-----	-----	-----	-----	-----
size of	-----	-----	-----	24	-----	-----
<i>Study of Man's Impact on the Climate, The</i>	-----	-----	-----	3	-----	-----
Stylosanthes	-----	-----	-----	75	-----	-----
Subalpine vegetation	-----	-----	-----	180	-----	-----
Subarctic Current	-----	-----	-----	-----	112, 119	-----
Subduction	-----	-----	-----	-----	-----	82
Subfossil carbon	xix, 182, 198, 280	-----	-----	-----	-----	-----
Subsidence	-----	-----	-----	-----	-----	74
Subsoils:	-----	-----	-----	-----	-----	-----
inability to sustain	-----	-----	-----	80	-----	-----
agriculture	-----	-----	-----	-----	-----	-----
Subtropical gyre	-----	-----	-----	-----	-----	115
Subtropics	-----	9, 119	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Successional dynamics	-----	-----	-----	45	-----	-----
Sucrose formation	-----	-----	-----	58	-----	-----
Sucrose phosphate synthase	-----	-----	-----	58	-----	-----
Suess effect	99, 152, 158	-----	-----	-----	-----	-----
Sugar accumulation in leaves	-----	-----	-----	68	-----	-----
Sugar beet	-----	-----	-----	61, 67, 78, 130	-----	-----
Sugarcane	-----	-----	-----	192	75	-----
Suicides: seasonal variation in	-----	-----	-----	-----	184	-----
Sulfates	-----	200	-----	-----	-----	-----
Sulfur	185, 194	-----	-----	-----	-----	-----
Sulfur-containing gases	-----	198-199	-----	-----	-----	-----
Sulfur cycle	185, 195, 202-203, 293, 299	-----	-----	-----	-----	-----
Sulfur dioxide	293	199	-----	xix, 6, 75, 199, 212	-----	-----
Sulfur flux	204	-----	-----	-----	-----	-----
Sulfuric acid	202	-----	-----	-----	-----	-----
Sulfuric acid aerosols	-----	44, 45, 182, 193	-----	-----	-----	-----
Summer drawdown	54	-----	-----	-----	-----	-----
Summer temperature anomalies	-----	-----	-----	-----	-----	39
Sun:						
angle of luminosity of	205	-----	-----	65	-----	-----
Sunflower	-----	-----	-----	158	75	-----
Sunlight	-----	-----	-----	-----	147	-----
Sunspot cycle	-----	202	-----	-----	-----	-----
Sunspot numbers	-----	-----	45	-----	-----	-----
Sunspots correlation of with climate change	-----	166, 202 167, 186	4, 45, 46	-----	-----	-----
Supercooling of ocean surfaces	-----	-----	-----	-----	-----	277
Supercooling relief	-----	-----	-----	-----	-----	124
Surface: slope of (glacial)	-----	-----	-----	-----	-----	168
Surface air temperature	-----	9, 276, 326, 329, 330, 331	-----	-----	-----	-----
carbon dioxide-induced change in	-----	xxi, 84, 87, 90-93, 106, 107, 140, 292, 313, 325, 330, 331, 332, 355, 356	-----	-----	-----	-----
change in changes in geographical distribution of	-----	74	-----	-----	-----	-----
distribution of	-----	100, 101, 115, 116, 117, 120, 121, 125-130, 140 87, 292	-----	-----	-----	-----

Surface air temperature

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Surface air temperature (continued)						
global mean	-----	10, 107, 142, 239, 271, 297, 357	-----	-----	-----	-----
land-ocean contrasts in latitudinal variation	-----	100, 102, 115	-----	-----	-----	-----
maximum global mean	-----	107	-----	-----	-----	-----
sensitivity of area mean	-----	314	-----	-----	-----	-----
simulated	-----	108	-----	-----	-----	-----
time series of	-----	114, 115, 121 151, 165	-----	-----	-----	-----
Surface albedo	-----	5, 32, 46, 62, 73, 86, 87, 91, 113, 137, 204, 216, 225, 290, 291, 296	115, 118, 182, 183	-----	-----	-----
impact on the climate of the	-----	216	-----	-----	-----	-----
Surface-albedo feedback	-----	88, 89, 144, 313-315, 316, 317	-----	-----	-----	-----
Surface boundary layer parameterization of the	-----	68, 323 77	-----	-----	-----	-----
Surface elevations of glaciers observations of	-----	-----	-----	-----	-----	162, 164-165, 168
Surface energy balance	-----	325-327	-----	-----	-----	-----
Surface load forcing	-----	-----	-----	-----	-----	97
Surface moisture (see Soil moisture)						
Surface of the Earth:						
energy flux at	-----	86, 285, 286, 291, 297	-----	-----	-----	-----
human effects on the characteristics of	-----	193	-----	-----	-----	-----
hydrology on the	-----	276	-----	-----	-----	-----
rate of evaporation at	-----	62, 69	-----	-----	-----	-----
roughness of	-----	73	-----	-----	-----	-----
warming of the	-----	87, 100, 140, 165, 206, 315, 327	-----	-----	-----	-----
Surface pressure data:						
monthly mean	-----	41	-----	-----	-----	-----
Surface roughness	-----	-----	-----	-----	101	-----
Surface strain rates (glacial)	-----	-----	-----	-----	-----	168
Surface supercooling (oceanic)	-----	-----	-----	-----	-----	277
Surface velocity (glacial)	-----	-----	-----	-----	-----	168, 185
Surface warming: amplification of	-----	-----	-----	-----	-----	41
Surface water (see also Hydrology; Hydrologic systems)	53, 90, 169	-----	-----	-----	27	-----
oversaturation with calcium carbonate of vertical stability of oceans'	102	-----	-----	-----	-----	-----
Surface water exchange	84	-----	-----	-----	-----	-----
Surface water organic carbon: net rate of export of	88	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
<i>Survey of Energy Resources</i>	72	-----	-----	-----	-----	-----
Sverdrup transport	-----	-----	-----	-----	-----	137
Swamp model	-----	90, 105, 139, 141	-----	-----	-----	-----
Sweet potato	-----	-----	-----	xxi, 67, 69, 103, 105-109, 130, 261-262	-----	-----
Sweet potato white flies	-----	-----	-----	140	-----	-----
Sweetgum	-----	-----	-----	69, 70, 90, 127, 134, 157, 158, 160, 179, 195	-----	-----
Swine	-----	-----	-----	-----	76	-----
Symbionts	-----	-----	-----	102	-----	-----
Synoptic activity: index of	-----	-----	121	-----	-----	-----
Synoptic data	-----	-----	-----	-----	-----	47
Synoptic disturbances	-----	91	-----	-----	-----	-----
Synthetic-aperture radar	-----	-----	-----	-----	-----	36, 43

T

Table Mountain Observatory	30, 56	-----	-----	-----	-----	-----
Tambora	-----	-----	44	-----	-----	-----
Tar sands	75	-----	-----	-----	-----	-----
Taxation	227, 228, 229, 243	-----	-----	-----	-----	-----
Technology: effects of	78, 177	-----	-----	-----	-----	-----
Tectonic activity	-----	-----	-----	-----	-----	76, 78-80, 95
Tectonic influences	-----	-----	171	-----	-----	-----
Tectonic motions	-----	-----	-----	-----	-----	13
Tectonic regions	-----	-----	-----	-----	-----	85
Tectonic trends	-----	-----	-----	-----	-----	82
TEEM	-----	-----	-----	43	-----	-----
Temperature (see also Air temperature; Temperature changes)	-----	-----	-----	-----	-----	139
air	-----	-----	39, 60, 61, 170, 175	5, 6, 13, 18, 22, 77, 81, 82	13, 15-18, 133	-----
hemispheric average	9	-----	-----	-----	-----	-----
latitude-altitude cross	90-92, 124-126,	-----	-----	-----	-----	-----
sections of differences in	129-130	-----	-----	-----	-----	-----
air-sea differences in	-----	-----	74-77, 98,	-----	-----	-----
analyses of air	-----	-----	99-100, 182	-----	-----	-----
	98	-----	98	-----	-----	-----

Temperature

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Temperature (continued)						
annual average:						
regional to global			169			
atmospheric,			xx, 57, 75			
averaging procedures for calculating mean			58			
cloud top		306	--			
comparison of land and marine			99			
correlation with salinity of			--			203
daily maximum and minimum			--	77, 81		
differences between			99-100			
surface-air and sea-surface			--			
effects of on plant growth			--	xviii, xxi, xxv, 73, 74, 76, 82, 109, 114, 178, 188		
effects of waste heat on surface		214	--			
estimates of for 6000 B.P.		247	--			
free-atmosphere			181-183			
global			6, 40, 46, 57, 99, 180			3, 268-269
global mean		239, 250	--		viii, 25	
ground		306	--			
hemispheric			38, 59, 64			
historical records of history of the past century		166, 222	36, 57-85, 174			
human health effects of instrumental record for land and ocean anomalies in surface-air		186	--		179, 184-189, 198	
land-based		239	--			
lapse rate of (see also Lapse rate)		88, 296, 316	--			
large-scale area-averaged surface-air			31, 57, 78, 81			
latitudinal and regional patterns of leaf		xxiii, xxiv, 262	--			
maps of past marine air		269	--	59, 63, 81, 194		
mean annual air			57, 98, 170			
mean surface measurement of	50		58, 59, 64, 132, 170			60, 202
methods of estimating hemispheric average		18				
nighttime marine air			38			
nocturnal			61-65, 75-76			
Northern Hemisphere:				76, 77		
land		18	--			
mean			xx, 31, 169			
over-the-ocean surface-air			xix, 31, 98			
plant tissue			--	81		
relationships to snowfall			119			246
sea-surface			77, 131, 262, 323, 355, 356			
estimates of latitudinal variation of seasonal changes in			xxviii, 39, 57, 75-76, 93, 96, 104, 182			
90, 98						
102, 104, 119, 265, 271						

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Temperature (continued)						
seasonal distribution of	266	-----	130	-----	-----	-----
seasonal trends of	-----	176	-----	-----	-----	-----
simulated changes in	-----	-----	-----	13, 81	-----	-----
soil	-----	-----	67, 72-74, 168	-----	-----	-----
stratospheric	-----	119, 262	-----	-----	-----	-----
structure of in the	-----	-----	60, 61, 165, 168	-----	-----	-----
atmosphere	-----	-----	57, 83, 98, 170,	-----	-----	-----
surface	-----	-----	182, 185	-----	-----	-----
surface-air	-----	-----	62, 63, 66	-----	97, 102, 105, 108	-----
variability of	-----	-----	-----	-----	15-16, 106	-----
surface-water (oceanic)	-----	-----	170	-----	-----	-----
time series of	-----	-----	39	-----	-----	-----
trends of	-----	-----	67, 69-72, 78, 168	-----	-----	-----
trends of over-ocean	-----	-----	-----	-----	-----	-----
tropospheric	-----	-----	218	-----	-----	-----
upper air	-----	8	-----	-----	-----	-----
variation in patterns of	-----	286, 292	-----	-----	-----	-----
vertical distributions of	-----	-----	-----	-----	-----	-----
zonal mean air	-----	90, 100, 116,	-----	-----	-----	-----
	-----	118, 119	-----	-----	-----	-----
Temperature and fossil fuel use	3	-----	-----	-----	-----	-----
Temperature anomalies	-----	152, 163, 183,	59, 73	-----	-----	-----
	-----	184	-----	-----	-----	-----
Temperature changes	3, 49, 134, 195	xx, 66, 90-93, 137	-----	-----	212	-----
Arctic	-----	-----	62, 78	-----	-----	-----
comparison of marine,	-----	-----	74-77, 98, 182	-----	-----	-----
land-based, and	-----	-----	-----	-----	-----	-----
free-atmosphere	-----	41	-----	-----	-----	-----
contribution of the weak	-----	-----	174	-----	-----	-----
absorption bands to	-----	-----	xxii, xxvii, 82,	-----	-----	-----
coupling of with sea level	-----	-----	85, 170	-----	-----	-----
decadal	-----	-----	-----	-----	-----	-----
effects of	-----	-----	-----	-----	xiv, 56-57,	-----
factors contributing to	-----	163-168	-----	-----	105-108, 114, 165	-----
global	-----	165	-----	-----	-----	-----
global and zonal mean	-----	138, 140	-----	-----	-----	-----
hemispheric	-----	-----	69, 72, 73, 77-79	-----	-----	-----
poleward amplification of	-----	21, 92, 173, 271,	-----	-----	-----	-----
	-----	276	-----	-----	-----	-----
rate of	-----	30	-----	-----	-----	-----
regional projections of	-----	-----	-----	209	-----	-----
regions of	-----	248	-----	-----	-----	-----
seasonal and latitudinal	-----	xxiii	171	-----	-----	-----
patterns of	-----	-----	-----	-----	-----	-----
simulated	-----	91, 124-130, 152,	-----	-----	-----	-----
	-----	176, 183, 184	-----	-----	-----	-----
stratospheric	-----	-----	73	-----	-----	-----
surface	-----	-----	80	-----	-----	-----
uncertainty in	-----	-----	65	-----	-----	-----
zonal mean surface	-----	xxi, 100	-----	-----	-----	-----
Temperature data (see also	-----	-----	31, 85	-----	-----	-----
Climate data)	-----	-----	-----	-----	-----	-----
daily mean	-----	-----	34	-----	-----	-----
inhomogeneities in:	-----	-----	-----	-----	-----	-----
land-based	-----	-----	32, 47	-----	-----	-----
ship-based	-----	-----	32	-----	-----	-----
spatial patterns of	-----	-----	63	-----	-----	-----

Temperature data

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Temperature data (continued)						
land-based monthly	-----	-----	32, 39, 47 34	-----	-----	-----
Temperature distribution in oceans	-----	-----	-----	-----	102	-----
Temperature extremes:						
acute effects of on humans	-----	-----	-----	-----	175, 198-200	-----
acute effects of on plants	-----	-----	-----	-----	75	-----
Temperature influences on female hormones	-----	-----	-----	-----	176	-----
Temperature instrumentation:						
history of	-----	-----	31	-----	-----	-----
Temperature recording stations	-----	-----	32	-----	-----	-----
Temperature records long-term	-----	17, 324	xix, 81-82	-----	13	47
Temperature/salinity diagrams	-----	-----	-----	-----	-----	120, 134-135, 203
Temperature-to-precipitation ratio	116	-----	-----	-----	-----	-----
Temperature variation: seasonal	-----	-----	-----	-----	28, 33, 209	-----
Temperature-water-vapor feedback: definition	-----	15-16	-----	-----	-----	-----
Tephra composition	-----	-----	44	-----	-----	-----
Tephra volume	-----	-----	42	-----	-----	-----
Termites	57	195	-----	-----	-----	-----
Terracing	-----	-----	-----	-----	80, 81	-----
Terrestrial ecosystems	19, 118-120, 143, 146-147, 161, 162, 169, 170, 265	-----	-----	-----	-----	-----
Terrestrial radiation balance of	-----	3, 31, 113 19	-----	-----	-----	-----
Tertiary Period	202, 205, 300	-----	-----	-----	-----	-----
Thaw depth	-----	-----	-----	148	-----	-----
Thermal damping (see also Thermal inertia)	-----	184, 267	-----	-----	-----	-----
Thermal diffusion	-----	157, 158, 171	-----	-----	-----	-----
Thermal expansion effect	-----	-----	137, 172, 174	-----	-----	-----
Thermal forcing	-----	134, 285	-----	-----	-----	-----
Thermal inertia	-----	8, 20, 102, 154	xxi, 96	-----	-----	-----
Thermal reservoirs of the climate system	-----	152, 156, 267	-----	-----	-----	-----
Thermal response time of oceans	-----	8, 20, 21, 102, 162, 175, 242, 262, 268, 276, 277	-----	-----	-----	-----
Thermal stress on the human body	-----	-----	-----	-----	176	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Thermal zones	-----	-----	-----	-----	85	-----
Thermoclines	83, 91, 148, 156, 144 179, 252	-----	-----	-----	102	107, 108, 110
density temperature relationship in fluctuations in the main oceanic ventilation	----- 157	-----	-----	-----	-----	-----
104	-----	-----	-----	-----	-----	114, 115
93, 169	-----	-----	-----	-----	-----	-----
Thermodynamic energy equations	-----	66, 294	-----	-----	-----	-----
Thermohaline: changes in properties of	-----	-----	-----	-----	123	-----
118, 120	-----	-----	-----	-----	-----	-----
Thermohaline circulation: atmospheric forcing of	83, 91	-----	-----	-----	-----	138
-----	-----	-----	-----	-----	-----	-----
Thermohaline overturning	-----	xxii, 156, 185	-----	-----	-----	-----
Thermometers	-----	-----	31	-----	-----	-----
Thermonuclear energy	71	-----	-----	-----	-----	-----
Thermonuclear testing (see also Nuclear testing; Tritium): injection of tritium into the atmosphere by	-----	-----	-----	-----	129	-----
Thermoperiods	-----	-----	-----	13	-----	-----
Thermoregulatory efficiency: human	-----	-----	-----	-----	187	-----
Thermoregulatory system	-----	-----	-----	-----	173, 199, 201, 212, 214, 215	-----
damage to	-----	-----	-----	-----	176, 184	-----
Thickness profiles (glacial)	-----	-----	-----	-----	-----	149-150, 320-324
Throughfall of precipitation: definition	-----	-----	-----	-----	26	-----
Thunderstorms	-----	9	-----	-----	-----	-----
Thwaites Glacier	-----	-----	-----	-----	-----	33, 53, 279-282, 301, 302
Tian Shan	-----	-----	-----	-----	-----	141, 223
Tibet	-----	-----	119, 132	-----	-----	-----
Tidal currents	-----	-----	-----	-----	113	-----
Tidal mixing	-----	-----	-----	-----	-----	123
Tidal record	-----	-----	-----	-----	-----	205
Tide gauge records	-----	-----	-----	-----	-----	74, 84, 92, 93, 94-97, 101
Tide gauges	-----	-----	-----	-----	-----	12, 73-90, 93, 95
Tides	190	-----	-----	-----	-----	-----
Tillage	-----	-----	-----	-----	44, 79, 80, 83, 216	-----
conservation	-----	-----	-----	-----	80, 84	-----
Tiller numbers	-----	-----	-----	83	-----	-----

Tillering

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Tillering	-----	-----	-----	132, 133, 134, 147, 207	-----	-----
Timber	116, 121, 125	-----	-----	-----	-----	-----
Timber demand	-----	-----	-----	-----	149	-----
Timber production	-----	-----	-----	-----	147, 149	-----
Time scale of the carbon dioxide climate problem	-----	156	-----	-----	-----	-----
Time scale of the effects on climate	-----	193	-----	-----	-----	-----
Time scale of the global mean transient response	-----	158, 173	-----	-----	-----	-----
Time scales of plant growth	-----	-----	-----	57, 134, 138, 140	-----	-----
Time series data:						
fisheries distribution	-----	-----	-----	-----	137	-----
temperature and sea ice	-----	152	-----	-----	-----	-----
Time-dependent forcing: climatic response to	-----	15, 20	-----	-----	-----	-----
Timing of stages of growth	-----	-----	-----	83, 134, 138	-----	-----
Tissue (plant):						
chemical composition of culture of	-----	-----	-----	xxii, 134	-----	-----
density of	-----	-----	-----	189, 200	-----	-----
mineral concentrations of	-----	-----	-----	83	-----	-----
quality of	-----	-----	-----	114, 211	-----	-----
synthesis of	-----	-----	-----	xxii, 134, 208, 212	-----	-----
Toolik Lake, Alaska	-----	-----	-----	79	-----	-----
Tornados:						
health effects of	-----	-----	-----	-----	189	-----
Trace gas emissions	293	-----	-----	-----	-----	-----
Trace gases	xvii, 3, 54, 57, 201, 217, 242, 243, 263, 282-283, 292, 293, 297, 298	3, 194-199, 205, 217, 222-223, 224, 262, 267, 271, 277	-----	-----	-----	-----
analysis of	40	-----	-----	-----	-----	-----
anthropogenic sources of	-----	xvii, 224, 263	-----	-----	-----	-----
band centers of	-----	30	-----	-----	-----	-----
chemical reactions of	-----	207, 268-269	-----	-----	-----	-----
climatic effects of	-----	21, 164-165, 206, 221, 224, 241, 263-264, 268	-----	-----	-----	-----
concentrations of	-----	xxiv, 5, 193	xxvii, 183	-----	-----	-----
effects of on ozone	-----	220	-----	-----	-----	-----
infrared absorption by	-----	xviii, xix, xxii-xxiii, 224	-----	-----	-----	-----
measurements of	56	-----	-----	-----	-----	-----
monitoring of	-----	277	183	-----	-----	-----
radiative properties of	-----	30, 41, 222, 262, 264, 268, 277	-----	13	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Trace gases (continued)						
radiatively active spectroscopic parameters for	-----	-----	26	-----	-----	41
Trace metals	-----	-----	-----	-----	44, 102, 105, 130, 134	-----
Tracers	29, 105-106, 150, 185 152, 299	-----	-----	-----	-----	-----
atmospheric chemical	146	-----	-----	-----	-----	-----
20, 90, 104, 169, 296, 299	-----	-----	-----	-----	-----	-----
distribution of isotopic	xxiii, 157, 169 20, 90-91, 100, 104, 105, 152, 204, 296, 299	-----	-----	-----	-----	-----
nonradioactive oceanic	90	-----	-----	-----	-----	-----
xviii, 89-90, 204, 258, 274	-----	-----	-----	-----	-----	-----
transient	xviii, 90, 93	-----	-----	-----	-----	-----
Trajectory analyses	145	-----	-----	-----	-----	-----
Transantarctic alpine glaciers: fluxes from	-----	-----	-----	-----	-----	194
Transantarctic Mountains	-----	-----	-----	-----	-----	185, 189, 319
Transfer function: definition	-----	18	-----	-----	-----	-----
Transient climatic effects	-----	152, 153-156, 169-184	-----	-----	-----	-----
Transient lag	-----	152	-----	-----	-----	-----
Transient models testing of	-----	169-184	-----	-----	-----	-----
-----	177-184	-----	-----	-----	-----	-----
Transient response model	-----	-----	81	-----	-----	-----
Transient Tracers in the Ocean	xxiii, 19, 90, 91-94, 102, 105, 157, 170, 204, 296, 299	-----	-----	-----	-----	129, 135
data from	-----	186	-----	-----	-----	-----
Translocation	-----	-----	-----	58, 120, 122, 145, 201	-----	-----
nocturnal	-----	-----	-----	59	-----	-----
photoassimilate	-----	-----	-----	58, 133	-----	-----
photosynthate	-----	-----	-----	5, 133	-----	-----
sucrose	-----	-----	-----	58, 113	-----	-----
Transmissivity of gases	-----	33	-----	-----	-----	-----
Transpiration	-----	73	-----	ix, 19, 43, 56, 61, 62, 103, 105-109, 193, 209, 221, 228, 233, 236, 241, 244, 257, 258, 269	19, 27, 28, 35, 40	-----
definition	-----	-----	-----	56	28	-----
effect of on photosynthesis	-----	-----	-----	56	-----	-----

Transpiration

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Transpiration (continued)						
leaf	-----	-----	-----	59, 60, 112, 193, 194, 197, 198, 199, 200, 208, 228	-----	-----
losses from rate of	-----	-----	-----	-----	39	-----
reductions in whole-canopy	-----	-----	-----	55, 60, 63, 72, 74, 76, 78, 82, 83, 84, 85, 87, 125, 127, 159, 208	-----	-----
Transport: offshore and onshore	-----	-----	-----	59, 89 xviii, 61-62, 86, 194	-----	-----
Transport of Carbon and Minerals in Major World Rivers Program	296	-----	-----	-----	-----	-----
Tree rings	xvii, 28, 32, 35, 37, 55, 56, 130, 160, 162, 163, 251, 263	62, 240	6, 47, 64, 160, 181	137, 180	11	224
isotopic ratios in	9, 20, 29, 36, 121, 130-131, 134, 159, 161-162, 192, 193, 252, 253, 295	-----	-----	-----	-----	-----
Trees:						
annual radial increment of growth factors of	-----	-----	-----	-----	158	-----
growth loss of growth of	-----	-----	-----	45, 180	151, 158 151	-----
depression of high-altitude growth rates of	-----	-----	-----	-----	149, 155, 161 151	147
harvesting of	-----	-----	-----	138	-----	-----
inventory data for	-----	-----	-----	-----	158	-----
life cycles of	-----	-----	-----	-----	147, 148, 214, 215	-----
longevity of	-----	-----	-----	-----	158	-----
maximum densities of	-----	-----	-----	-----	149, 150	-----
maximum growth potential of	-----	-----	-----	-----	147	-----
mortality of	-----	-----	45	-----	-----	-----
catastrophic	-----	-----	-----	-----	152	-----
chronic	-----	-----	-----	-----	151	-----
rates of	-----	-----	-----	-----	163, 165	-----
natural history data for	-----	-----	-----	-----	220	-----
pathogens of	-----	-----	-----	-----	155, 156, 159, 161, 212, 214	-----
regeneration of	-----	-----	45	-----	-----	-----
reproduction of	-----	-----	-----	-----	147, 155	-----
senescence and mortality of	-----	-----	-----	-----	151, 155	-----
species competition of	-----	-----	-----	-----	149-150, 162	-----
species migration of	-----	-----	-----	-----	150, 152	-----
stands of:	-----	-----	-----	121	151	-----
single-species	-----	-----	-----	-----	-----	-----
tropical	-----	-----	-----	-----	77	-----
Trefoil	-----	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Trench processes	-----	-----	-----	-----	-----	80
Triazine herbicides	-----	-----	-----	169	-----	-----
Trent Glacier	-----	-----	-----	-----	-----	217
Triose phosphate	-----	-----	-----	58, 59	-----	-----
Tritium	91, 99, 106, 156, 179 169	-----	-----	-----	-----	-----
oceanic	-----	-----	-----	-----	-----	129
Tritium data	xviii, 94, 100	-----	-----	-----	-----	-----
Tritium penetration	93, 100, 148	-----	-----	-----	-----	-----
Trophic interactions	-----	-----	-----	-----	133	-----
Trophic levels	-----	-----	-----	-----	103	-----
higher	-----	-----	-----	-----	118-119	-----
lower	-----	-----	-----	-----	116-118	-----
Tropical oceans	48	-----	-----	-----	108	-----
warming of	-----	287, 323	-----	-----	-----	-----
Tropics	-----	88, 98	-----	-----	14	-----
extension of boundary of	-----	-----	-----	-----	173	-----
Tropopause	-----	94	-----	-----	-----	-----
definition	-----	208	-----	-----	-----	-----
radiative fluxes at	-----	xix, 41, 43, 264, 348	-----	-----	-----	-----
Troposphere	36, 45	-----	-----	-----	-----	-----
aerosol loading of the	-----	-----	169, 174	-----	-----	-----
carbon dioxide-induced	-----	86, 92, 267, 270,	21, 166, 171	-----	-----	-----
temperature change in the	-----	286	-----	-----	-----	-----
characteristics of	-----	46	-----	-----	-----	-----
aerosols in the	-----	223	-----	-----	-----	-----
chemistry of the	-----	50	-----	-----	-----	-----
cooling of	-----	264	-----	-----	-----	-----
coupling between the upper	-----	264, 324, 333	-----	-----	-----	-----
and lower	-----	-----	-----	-----	-----	-----
coupling with Earth's	-----	-----	-----	-----	-----	-----
surface	-----	-----	-----	-----	-----	-----
definition	-----	6	-----	-----	-----	-----
heating rates of the	-----	35, 333	-----	-----	-----	-----
hemispheric average	-----	-----	38	-----	-----	-----
temperatures of the	-----	-----	-----	-----	-----	-----
lapse rates of the	-----	-----	71, 175	-----	-----	-----
radiative budget of	-----	40	-----	-----	-----	-----
radiative emissions to	-----	270	-----	-----	-----	-----
space of	-----	-----	-----	-----	-----	-----
temperature fluctuations	-----	-----	70, 71	-----	-----	-----
in the	-----	-----	-----	-----	-----	-----
temperatures in the	-----	-----	67, 69-72, 78, 168	-----	-----	-----
upper	-----	98, 290	-----	-----	-----	-----
warming of the	-----	87, 91, 98, 100, 125, 140, 302, 315	-----	-----	-----	-----
Tulip poplar	-----	-----	-----	162	-----	-----
Tuna	-----	-----	-----	-----	98, 127	-----
Tundra	117, 119, 180, 200	-----	118, 119	xix, xxii, 14, 45, 120, 125, 129, 133, 135, 137, 138, 141, 144, 147, 148	-----	-----

Turbidity

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Turbidity	-----	-----	-----	-----	44	-----
Turbulence (oceanic)	-----	179	-----	-----	97, 101, 102, 108-109, 111, 114-116, 123, 124, 125, 128, 130-132, 134, 135, 139, 212, 214, 215	-----
Turbulent mixing of oceans	105, 143	179, 180	-----	-----	-----	-----
Turgor pressure	-----	-----	-----	55, 56, 87, 112, 113, 127, 129, 209	-----	-----
Turnover coefficients	188	-----	-----	-----	-----	-----
Turnover times	119-120, 158-159, 182-190, 202	-----	-----	-----	-----	-----
Typhoid fever	-----	-----	-----	-----	193	-----

U

Umbral/penumbral ratio	-----	-----	46, 84	-----	-----	-----
Umkehr data	-----	217, 218	-----	-----	-----	-----
Uncertainty analysis	23, 223, 272-276, 281-282	339-340, 346-347, 358-361	-----	-----	128	-----
Understory plants	-----	-----	-----	176, 178	-----	-----
Uniformitarianism	185	-----	-----	-----	-----	-----
Union of Soviet Socialist Republics	294	244, 247	38, 42	-----	90, 125, 147	-----
United Kingdom	-----	-----	42	-----	-----	-----
United Kingdom Central Electricity Research Laboratories	-----	-----	-----	14, 24	-----	-----
United Kingdom Meteorological Office	-----	-----	40, 41	-----	-----	-----
United Nations	18	-----	-----	-----	-----	-----
United Nations Environment Programme	17, 116, 121, 123, 124, 133, 242, 296	-----	-----	-----	-----	-----
United Nations Statistical Office	18, 65-66	-----	-----	-----	-----	-----
United States	229, 294	214, 248	34, 38, 42, 64, 117, 153-156, 160	-----	34, 79, 82, 97	76, 94-97
economy of: agricultural component of	-----	-----	-----	-----	71	-----
United States Bureau of Reclamation	-----	-----	-----	-----	48	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
United States Department of Agriculture Animal and Plant Health, Inspection Service	-----	-----	-----	-----	85	-----
United States Environmental Protection Agency	-----	170, 174	-----	-----	-----	-----
United States Forest Service	-----	-----	-----	-----	158	-----
United States Geological Survey	18, 74	-----	-----	-----	-----	181, 235
University of British Columbia	-----	-----	-----	14	-----	-----
University of Florida	-----	-----	-----	13	-----	-----
University of Nottingham	-----	-----	-----	14, 25	-----	-----
Unmanaged ecosystems	-----	-----	-----	xxii, xxiv, 7, 13, 24, 101, 119, 133, 145, 147, 207, 209	-----	-----
Uplift	184	-----	-----	-----	-----	-----
Upper air analyses	-----	-----	41	-----	-----	-----
Upper air data	-----	-----	85	-----	-----	-----
Upper air data network	-----	-----	70	-----	-----	-----
Upper air pressures, winds, and temperatures	-----	-----	xix, 41	-----	-----	-----
Upper air stations	-----	-----	182	-----	-----	-----
Upwelling	19, 41, 48, 49, 50, 52, 53, 84-85, 92, 95, 148, 150, 156, 179, 191	156, 158, 276	-----	-----	101, 103, 108, 109, 115, 116, 123, 125, 127, 128, 136, 154	275
effects of transient surface temperatures on equatorial	-----	182	-----	-----	-----	-----
-----	-----	185	-----	-----	-----	-----
Upwelling water: nutrients in	105	-----	-----	-----	-----	-----
Ural Mountains	-----	-----	-----	-----	-----	141
Urban heat island effects	-----	213	-----	-----	-----	-----
Urban structure design: health effects of	-----	-----	-----	-----	188	-----
Urban warming	-----	-----	35	-----	-----	-----
Urbanization	-----	v, 62, 200, 203	v, xx, 32, 34, 45, 170, 181	v, 137	43, 72, 187, 196	-----
heat stress and	-----	-----	-----	-----	187-188	-----
Ürümqi (Ürümqihe) Glacier	-----	-----	-----	-----	-----	35, 223

V

Validation (see Models, validation of)

Validation data set

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Validation data set	-----	-----	-----	82-83	-----	-----
Van Helmont	-----	-----	-----	36	-----	-----
Vapor pressure	-----	-----	-----	-----	27	-----
Vapor pressure deficit	-----	-----	-----	77, 78, 126	28	-----
Vapor pressure difference: leaf to air	-----	-----	-----	59	-----	-----
Vapor pressure profiles	-----	-----	-----	66	-----	-----
Vapor transfer resistance: leaf	-----	-----	-----	59	-----	-----
Variability: seasonal	190	-----	-----	-----	-----	-----
Variegated Glacier	-----	-----	-----	-----	-----	51, 315
Varietal development	-----	-----	-----	-----	72	-----
Varves	-----	18	-----	-----	-----	-----
Vascular lesions	-----	-----	-----	-----	179	-----
Vascular plants	-----	-----	-----	145	-----	-----
Vector-borne diseases: meteorological factors in	-----	-----	-----	-----	193, 199, 212	-----
Vectors of human disease	-----	-----	-----	-----	39	-----
Vectors of parasites	-----	-----	-----	-----	194, 199	-----
Vegetation	115, 156, 163, 187, 199, 291, 300	-----	-----	-----	-----	-----
carbon storage by changes of hydrologic repercussions of decay of effects on climate of height of predicted response to elevated carbon dioxide of	117, 121	-----	-----	-----	v, xiii 35, 55	-----
propagation of shifts in boundaries of tropical forest	117	193, 225, 313	-----	-----	70, 190	-----
Vegetation canopy	-----	204-205, 216	-----	-----	24	-----
clearing of rate of adjustment of regulating role of in moisture and energy fluxes structure of	-----	-----	-----	-----	3, 4, 27, 35, 37, 38, 45, 47, 53-91, 101-115, 119-148, 161-162, 175, 178-179, 189, 198, 207, 209	-----
Vegetation distribution projections	-----	-----	-----	-----	165 200	-----
Vegetation index	50	-----	-----	-----	27, 28, 59, 213, 218	-----
Vegetation management	-----	-----	-----	-----	62 31 55	-----
Vegetation responses	-----	-----	-----	ix, 3, 36, 56	vii, viii, xvi, xix, 4, 19, 20,	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Vegetation responses (continued)					32, 35, 36, 38, 39, 41, 42, 43, 209, 210, 218	
forests'					150-151, 155, 161-162	
Vegetative cover		7, 63, 73, 262				
Vegetative exudation	119					
Velocity: glacial-surface						168, 185
Velocity gradients (glacial)						327
Velocity profiles (glacial): flow line						207, 294-295, 319, 320-324
Velocity vectors (glacial)						182, 190, 193, 207
Velvetleaf				131, 157, 158, 159, 160, 162		
Verde River					46	
Verification (see Models, verification of)						
Vertical diffusivities	100					
Vertical eddies		158, 171, 178, 181				
Vertical energy balance models (see Models, radiative convective)						
Vertical mixing of the atmosphere		6				
Very High Resolution Radiometer and Nimbus microwave data			122			
Vienna Meteorological Congress			32			
Viet Nam					193	
Viking period		17, 241, 269				
Vineyards				14		
Viral diseases: animal					191	
Epstein-Barr					183	
human					199	
airborne					190-192	
Viral dispersal					190	
Viral survival: meteorological factors in					191, 201	
Virginia: forests of	125					
Viscoelastic creep		163				
Viscoelastic field theory						15
Volcanoes	31, 193, 194	44, 59, 170, 182, 183, 199, 213,	43, 68, 70, 73, 84			73

Volcanoes

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Volcanoes (continued)	-----	265	-----	-----	-----	-----
aerosols from	-----	xviii, 44, 45, 46, 186, 198, 199, 267, 268	xix, xxvii, 42, 47, 169	-----	-----	-----
effects on climate of	-----	xxii, 21, 163, 167-169, 171, 184	31, 45, 83, 165, 184	-----	-----	-----
eruptions of	34, 87, 188, 202	167, 182, 199-200, 213, 222, 268, 278	xxii, 4, 42-45, 68, 70, 73, 84, 165, 175	-----	13	-----
catalog of injections of sulfur- containing gases by	-----	44, 213	42, 169	-----	-----	-----
Volcanic cooling	48	-----	-----	-----	-----	-----
Volcanic explosivity index (VEI)	-----	-----	43, 44	-----	-----	-----

W

Walruses	-----	-----	-----	-----	105	-----
Ward Hunt Ice Shelf	-----	-----	-----	-----	-----	23, 24, 145, 148
Warm-adapted species	-----	-----	-----	201	-----	-----
Warm air advection	-----	-----	118	-----	-----	-----
Warming (see also Temperature changes): amplification of surface global	-----	-----	-----	35	-----	41
3, 11, 32, 182, 242	-----	-----	-----	-----	-----	-----
Warming trends (see also Temperature changes)	-----	-----	xxi, 57, 60, 61, 70, 170	-----	-----	-----
Washington State	-----	-----	-----	-----	-----	143
Waste heat	-----	203, 213-214, 221, 223	-----	-----	-----	-----
definition	-----	203	-----	-----	-----	-----
effects of	-----	213	-----	-----	-----	-----
release of	-----	193, 225	-----	-----	-----	-----
Wastewater	-----	-----	-----	-----	34, 37	-----
Wastewater spray irrigation	-----	-----	-----	-----	190	-----
Water (see also Surface water): generating electricity with residence time on the continental shelf of salinity of (see also Salinity) transport of	-----	-----	-----	-----	25	-----
-----	-----	-----	-----	-----	21	-----
-----	-----	-----	-----	45, 59	-----	-----
-----	-----	-----	-----	-----	124	-----
Water access and ownership: legal definitions of	-----	-----	-----	-----	37	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Water allocation practices	-----	-----	-----	-----	59	-----
Water availability	-----	-----	-----	-----	25, 28, 60-61, 83, 200, 212	-----
coincidence with demand for health effects of surface	-----	-----	-----	-----	31	-----
-----	-----	-----	-----	-----	195	-----
-----	-----	-----	-----	-----	27, 49-51	-----
Water balance: regional estimates of seasonal	-----	-----	-----	-----	60	-----
Water-balance method	-----	-----	-----	63	-----	-----
Water chemistry: changes in	-----	-----	-----	-----	105, 134	-----
Water columns: stratification of	-----	-----	-----	-----	-----	124
Water conservation	-----	-----	-----	-----	34, 51, 82, 83	-----
Water consumption	-----	-----	-----	-----	32	-----
Water demand economic factors in patterns of price and income sensitivity of	-----	-----	-----	-----	25, 31, 58, 59	-----
-----	-----	-----	-----	-----	57	-----
-----	-----	-----	-----	-----	50, 57, 61	-----
-----	-----	-----	-----	-----	57	-----
Water demand in densely populated areas	-----	-----	-----	-----	34	-----
Water diversion	-----	-----	-----	-----	82	-----
Water effects on plants	-----	-----	-----	139, 193	-----	-----
Water hyacinth	-----	-----	-----	-----	39	-----
Water-logging of soils	-----	-----	-----	-----	32, 83	-----
Water losses	-----	-----	-----	-----	39, 49, 59	-----
Water management irrigated-system practices for rainfed agriculture	-----	-----	-----	-----	81-83	-----
-----	-----	-----	-----	-----	82-83	-----
-----	-----	-----	-----	-----	34	-----
-----	-----	-----	-----	-----	81-82	-----
Water-mass formation	-----	-----	-----	-----	-----	66
Water-mass volumes: differences in	-----	-----	-----	-----	-----	110
Water needs	-----	-----	-----	-----	85	-----
Water plants (see also Aquatic plants)	-----	-----	-----	-----	39, 59, 217	-----
Water potentials: tissue	-----	-----	-----	126, 127, 162, 209	-----	-----
Water prices (see Water demand, price and income sensitivity of)	-----	-----	-----	-----	-----	-----
Water quality: decline of health effects of salinity problems in	-----	-----	-----	-----	38	-----
-----	-----	-----	-----	-----	195-196, 200, 212	-----
-----	-----	-----	-----	-----	45, 59	-----
Water resources (see also Water use)	-----	279	-----	197	xv, 6, 25-62, 212-218, 219, 221	-----

Water resources

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Water resources:						
detection of carbon dioxide-buildup effects on distribution issues of human health and instream uses of issues about nonclimatic determinants of offstream uses of reuse of scope of potential impacts on	-----	-----	-----	-----	54 32 175, 195 37 31-59, 212-218 32 37 32, 82 34-35, 37, 38, 39, 40, 42, 43, 44, 46	-----
sensitivity of to changes in climate and vegetation responses	-----	-----	-----	-----	32-33, 36, 38, 39, 40, 41, 42, 43, 45	-----
supply issues of utilization of	-----	-----	-----	-----	30, 32, 81, 195 33-34	-----
Water runoff (see also Runoff):						
carbon dioxide-induced changes in	-----	-----	-----	-----	32	-----
Water shortages (see Water availability; Water resources, supply issues of)						
Water status of plants:						
internal	-----	-----	-----	194, 200, 201	-----	-----
Water storage						
economics of surface	-----	-----	-----	-----	30, 38-39, 53, 214, 215, 216 83 52-53, 72, 82	-----
Water storage systems:						
efficiency of losses from	-----	-----	-----	-----	37 39, 40, 49, 59, 212	-----
Water stress						
	-----	-----	-----	25, 63, 74, 111, 112, 113, 127, 129, 161, 169, 176, 177, 182, 188, 193, 194, 195, 198, 199, 201	-----	-----
Water supply (see also Water availability; Water resources, supply issues of)						
surface	-----	-----	-----	-----	36, 59, 88 32, 59, 212, 213, 214, 217	-----
Water system vulnerability						
Water table						
Water transfers:						
interbasin	-----	-----	-----	-----	37	-----
Water treatment						
Water use					ix, 13, 23, 63, 66, 74, 76, 83, 112, 125-127, 134, 139, 157, 35	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Water use (continued)	-----	-----	-----	169, 193, 200, 208, 209, 211	-----	-----
agricultural conflicts in	-----	-----	-----	-----	72	-----
pattern changes in technology of unknowns in future of	-----	-----	-----	-----	37-39, 59, 212, 213	-----
Water-use efficiency (plants)	-----	-----	-----	-----	53	-----
definition	-----	-----	-----	-----	34, 57	-----
Water vapor	-----	3, 5, 6, 27, 29, 40, 51, 87, 197-198, 263, 269, 270, 291, 296, 326, 330, 332, 333	4, 16, 167	-----	3, 28, 35, 36, 75, 151	-----
abundance in atmosphere of atmospheric	-----	43, 315, 330	-----	-----	-----	40
atmospheric mixing ratio of budget of	-----	86, 198, 291, 313	-----	-----	-----	-----
continuity equation for emissivity of	-----	198	-----	-----	-----	-----
radiative properties of	-----	66	-----	-----	-----	-----
stratosphere-troposphere exchange of	-----	17	-----	-----	-----	-----
stratospheric transport of	-----	xviii, 30, 31, 35, 50, 198, 262	-----	-----	-----	-----
tropospheric variation in abundance of	-----	198	-----	-----	-----	-----
vertical profiles of	-----	198	-----	-----	-----	-----
Water-vapor absorption (see also Longwave radiation)	-----	7, 98, 99, 135, 265	-----	-----	-----	-----
Water-vapor continuum	-----	197, 205	-----	-----	-----	-----
Water-vapor feedback	-----	43, 315, 330	-----	-----	-----	-----
Water vapor mixing ratio	-----	137, 153, 329	-----	-----	-----	-----
Water vapor pressure	-----	30, 294	-----	-----	-----	-----
Water-vapor/temperature feedback	-----	297, 298, 299, 309, 317, 330, 355	182	-----	-----	-----
Water volume of the oceans	-----	65, 88, 89, 107, 141, 155	13	-----	27	-----
Water yield	-----	119, 139	-----	-----	-----	101
Watersheds effects of human activities on	-----	-----	-----	40	-----	-----
	-----	-----	-----	62	-----	-----

Wave action

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Wave action	-----	-----	-----	-----	102	246
Weather:						
changes in definition patterns of regional simulations of synthetic data set of	-----	xviii, 4	-----	7	131, 175, 210 12	-----
Weather fronts and disease onset	-----	-----	-----	47, 77, 196	-----	152
Weather information systems: agricultural	-----	-----	-----	-----	114 14	-----
Weather station location	-----	-----	33-34, 170	-----	-----	-----
Weather variables: effects on human health of	-----	-----	-----	-----	175, 179-190, 197	-----
Weathering	xvi, 31, 192, 193, 194, 195, 203, 258, 299, 300	-----	-----	190	-----	-----
Weathership P	-----	-----	-----	179	-----	-----
Weatherships: ocean	-----	-----	98	-----	-----	-----
Weddell Sea	-----	-----	124, 125	-----	-----	5, 20, 21, 31, 116, 118, 197, 207, 314
Weddell Sea Polynya	-----	-----	-----	-----	-----	116
Weed control	-----	-----	-----	191	72	-----
Weed-crop competition	-----	-----	-----	x, 140, 157, 161, 169, 191-192	-----	-----
Weed-to-crop ratios	-----	-----	-----	158	-----	-----
Weeds water	-----	-----	-----	xvii, 113, 201	19, 80, 212 39	-----
West Antarctic Ice Sheet	-----	-----	xxiv, xxviii, 133, 135, 139, 173	-----	-----	4, 53-58, 63, 99, 121, 282-286, 311
environment of model of retreat of	-----	-----	-----	-----	-----	47 188
shrinkage of stability of	-----	-----	-----	-----	-----	9, 10, 188, 317-328
West Antarctic flow	-----	-----	-----	-----	-----	46, 53-58, 282
West Antarctic input	-----	-----	-----	-----	-----	46, 48, 271, 280
West Antarctica environment of	-----	-----	-----	-----	-----	185
Western Boundary Undercurrent	94	-----	-----	-----	-----	186-188
Wet basins	-----	-----	-----	-----	51, 94, 175, 301 46	-----
Wetlands	117, 197, 198	-----	-----	-----	-----	-----
coastal marine	198, 255	-----	-----	-----	-----	-----
freshwater	253, 255	-----	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Whales	-----	-----	-----	-----	107, 118, 127	-----
Wheat	-----	-----	-----	xxi, 24, 57, 67, 68, 71, 73, 74, 90, 105-109, 111, 112, 129, 132, 133, 176, 177, 178, 195, 196, 263-272	75, 76, 77	-----
Wheat belt shift of	-----	-----	-----	-----	72, 80 79	-----
Wheat production: government control of	-----	-----	-----	-----	79	-----
Wheat regions	-----	-----	-----	197	-----	-----
Wheat varieties	-----	-----	-----	-----	72	-----
White Glacier	-----	-----	-----	-----	-----	24, 146, 148
White Mountains of Eastern California	-----	-----	-----	180	-----	-----
Whole-canopy responses vs leaf level responses	-----	-----	-----	xxi, 64-66	-----	-----
Whole-crop responses	-----	-----	-----	xxi, 28	-----	-----
Whole-plant responses: first-order (physiological) second-order (ecological)	-----	-----	-----	5, 141 5, 141	-----	-----
Wilting	-----	-----	-----	-----	41	-----
Wind change of effects on ocean circulation of erosion effects of monthly mean patterns of surface	257 ----- 165 ----- 92, 166	66, 99, 205 ----- 269 -----	118 102	21, 66, 77 ----- -----	-----	47
Wind damage: agricultural trees'	-----	-----	-----	-----	214 156, 165, 214, 215	-----
Wind direction distributions	-----	-----	-----	-----	103, 115	-----
Wind-driven transport of sea water	-----	-----	-----	-----	-----	137
Wind energy	71, 78	-----	-----	-----	-----	-----
Wind forcing: katabatic	-----	-----	-----	-----	-----	66
Wind patterns	-----	-----	-----	-----	97, 103, 116, 125, 131	50, 124
Wind speed and direction changes	-----	-----	-----	-----	100, 103, 139	-----
Wind stress	20, 48, 49, 57, 93, 169, 296, 299	-----	102, 125, 126	-----	102, 103, 125	-----
Wind throw of trees	-----	-----	-----	138	-----	-----
Wind velocity	93	48, 63	-----	76	27, 103, 114, 116, 198-200	-----

Windblown soil and sand

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Windblown soil and sand	-----	200	-----	-----	-----	-----
Windbreaks	-----	-----	-----	-----	80, 83	-----
Window region: absorption in the	-----	50	-----	-----	-----	-----
Winter crops	-----	-----	-----	77	-----	-----
Wolf minimum	-----	-----	46	-----	-----	-----
Wolverine Glacier	-----	-----	136	-----	-----	35, 223, 246
Wood:						
density of fuel	-----	-----	-----	86	-----	-----
78, 163	-----	-----	-----	-----	-----	-----
harvest of fuel	127, 267	-----	-----	-----	-----	-----
production of	126, 127, 202, 266	-----	-----	137, 181	-----	-----
Woods Hole Oceanographic Institution	92	-----	-----	-----	-----	-----
Wordie Ice Shelf	-----	-----	-----	-----	-----	31, 199
ice front position of	-----	-----	-----	-----	-----	199-201
Workshop on Anticipated Plant Responses to Global Carbon Dioxide Enrichment	-----	-----	-----	3	-----	-----
World Climate Research Programme	-----	-----	182	-----	60	-----
World economy: fluctuations in	67	-----	-----	-----	-----	-----
World Energy Conference	72	-----	-----	-----	-----	-----
World Glacier Inventory	-----	-----	-----	-----	-----	34, 42, 67, 217, 228
World Glacier Monitoring Service	-----	-----	-----	-----	-----	67, 253
World Meteorological Organization	17, 30, 55, 242	-----	32	-----	-----	-----
World Ocean Circulation Experiment	xxiii, 299	275	182	-----	-----	-----
World Resources Institute	242	-----	-----	-----	-----	-----
World Weather Records	-----	-----	33, 36, 40, 152, 153	-----	-----	-----
World Weather Watch	-----	-----	182	-----	-----	-----
Worldwatch Institute	241	-----	-----	-----	-----	-----
Würm Glaciers	-----	-----	-----	-----	-----	85
Würm-Wisconsin ice	-----	-----	-----	-----	-----	92, 93, 94, 101

XYZ

Xenon lamps	-----	-----	-----	82	-----	-----
Xerothermal	-----	250	-----	-----	-----	-----

	Global Carbon Cycle	Projecting Climatic Effects	Detecting Climatic Effects	Direct Effects	Information Requirements for Studies	Glaciers and Sea Level
Year-class strength of fish	-----	-----	-----	-----	109, 130, 133, 135	-----
Yellowfin sole	-----	-----	-----	-----	106-107, 112, 118, 120-121, 124, 139, 140	-----
Yukon River	-----	-----	-----	-----	114	-----
Zonal Air Pollution System	-----	-----	-----	14, 24, 25	-----	-----
Zooplankton	-----	-----	-----	-----	107, 118, 123, 125	-----
Zurich relative sunspot number	-----	-----	45	-----	-----	-----