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CHARACTERIZATION OF INFORMATION REQUIREMENTS FOR STUDIES OF CO₂ EFFECTS: WATER RESOURCES, AGRICULTURE, FISHERIES, FORESTS AND HUMAN HEALTH

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PREFACE

The increase in atmospheric carbon dioxide (CO₂) has the potential to alter the Earth's climate and vegetation, which in turn may have significant impacts on the global environment. The goal of the U.S. Department of Energy's Carbon Dioxide Research Program is to identify possible policy options for government action in response to these potential changes. To identify these options, the indirect effects—that is, the subsequent consequences of CO₂-induced changes in climate and vegetation—must be examined and understood.

Many potential indirect effects can be identified. This report focused on five elemental areas—water resources, agriculture, fisheries, forests, and human health. The objective of this report was to establish a baseline of knowns and unknowns and delineate the data and improvements in methodology required to estimate the impacts on humankind from increased atmospheric CO₂. To be able to conduct future, regional impact studies, this effort has concentrated primarily on defining the data required from CO₂ research, that is, carbon cycle, climate, and vegetative response. Although there are a few unique data requirements, the primary data required for all five study elements is similar. Projections are required of future rates of increase in atmospheric CO₂ concentration; the rate, magnitude, and variability of regional and seasonal climate change; how vegetation will respond to CO₂-induced changes; and importantly, what the interactive effects of a changed climate and vegetation response will be. It is critical that this information be available in terms of various regions as defined, for example, by crop zones or drainage basins. This is because the potential indirect effects will vary around the world by such regions.

Important progress has been made in the last decade toward providing the data necessary for indirect effects research. Knowledge of past atmospheric CO₂ concentrations has improved markedly. Projections of future CO₂ concentrations now include more accurate representations of the exchanges of carbon among the atmosphere, the oceans, the cryosphere, and the biosphere. Increasingly complex models that incorporate more realistic representations of oceans, geography, and the seasonal cycle are providing more specific theoretical projections of the potential climate and vegetation changes. There also has been a substantial expansion of the data base needed to search for the predicted climate changes. Finally, some CO₂-specific field and laboratory experiments appear to indicate that some natural ecosystems and crops may benefit from the higher atmospheric CO₂ levels. However, it is the sum of, and interactions of, climate change and vegetation that will ultimately determine effects on vegetation.

While there have been many advances, much remains to be done. Virtually all theoretical studies suggest that increasing CO₂ concentrations would significantly

increase average global temperatures. However, such a warming is not yet clearly identifiable in the observational record, even though CO₂ concentrations have risen about 25% since the middle of the last century. In addition, data and modeling efforts are lacking in terms of details about (1) regional and seasonal climate changes and (2) interactions between CO₂-induced climate and vegetation changes. For example, better understanding, theoretical modeling, and data are needed about how the amount of precipitation and the density of vegetation cover determine surface runoff into streams before an assessment can be made of how a CO₂-induced change in these variables would change surface runoff. Without improvements in each discipline area, as well as the direct effects research, indirect effects studies will not be able to predict seasonal changes on regional scales. Thus, comprehensive assessment of the potential indirect effects of climate and vegetation changes on natural and agricultural ecosystems is not yet possible.

A sincere thanks goes to Margaret R. White, Lawrence Berkeley Laboratory, for her contribution to this document as editor and author. The contributing authors are to be commended for the dedication involved in writing for this report.

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EDITOR'S PREFACE

There has been widespread concern within the scientific community that should carbon dioxide (CO₂) build-up in the atmosphere result directly in climate and vegetation changes, these changes in turn might have effects (termed indirect effects) that would have consequences on human welfare. Many of these potential indirect effects have been pointed out in numerous publications on CO₂ issues and were the subject of workshops organized by the American Association for the Advancement of Science (AAAS) and supported by the U.S. Department of Energy (DOE).

The State-of-the-Art volumes on carbon cycle, climate change, and vegetation response describe the current knowledge and research related to the causes and direct effects of increasing atmospheric CO₂. Although much progress has been made in this research, current knowledge is not yet adequate for quantifying the indirect effects of CO₂ increase. However, it was DOE's perception that some of these effects should be investigated, with the aim of determining the data, information, and research that would be needed for quantifying the indirect effects when the direct effects become more precisely defined. Because all the possible effects could not be investigated, it was decided to select a few rather broad fields that were deemed critical to human welfare and would provide a basis for future studies. The fields selected were water resources, agriculture, fisheries, forests, and human health.

Researchers with special expertise in these fields were asked to write comprehensive reports with respect to the relationships of climate and vegetation change to their field. They were to examine current knowledge and research and determine the data and new or modified research, both from other CO₂ research programs and within their fields, necessary for quantifying the indirect effects of increased atmospheric CO₂.

To ensure that nothing major had been overlooked or over- or underemphasized, these reports were extensively peer reviewed. The authors then modified their reports on the basis of pertinent suggestions by the reviewers. However, it was the responsibility of the authors to determine the final content, and the conclusions expressed in the chapters are solely those of the authors.

It was not possible to cover all the worldwide literature regarding pertinent issues in these fields nor to tabulate all the available applicable data. In addition, to keep the length of the chapters within reasonable bounds, all the pertinent supporting data and references could not be included. However, we feel that the coverage that was possible has identified many of the major deficiencies in knowledge regarding the generic problems in these fields as well as the research and data needs for future studies.

I am particularly grateful to the chapter authors for their diligence in preparing these chapters and the technical reports that support the information in the chapters and for their patience throughout the prolonged review, rewrite, and editorial process. The able assistance and patience of two secretaries, July Barule and Tennessee Gock, at Lawrence Berkeley Laboratory, in preparing and revising some chapters is truly appreciated. The editorial and organizational talent of the MAXIMA Corporation has been very valuable in preparing the volume for publication. In particular, our thanks go to Nancy Brown, Jon Findley, Ann Marie Mitroff, and Michael Madden. We would also like to thank Fred and Linda O'Hara of Oak Ridge, Tenn., for indexing the volume and Michael O'Hara for performing the makeup. Guidance from the DOE Carbon Dioxide Research Division, Frederick A. Koomanoff, Director, and Michael R. Riches, Program Manager, has been invaluable.

Margaret R. White
Editor

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EXECUTIVE SUMMARY

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.

1. OBJECTIVES OF THE CURRENT STUDY OF INDIRECT EFFECTS

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This report discusses the potential indirect effects of changes in climate and vegetation response resulting from increased levels of carbon dioxide (CO₂) in the atmosphere. There are currently many uncertainties in the scientific data base related to CO₂; thus, it is not possible, at this time, to quantify the indirect effects of CO₂ increase. The current urgent requirements are definitions of the data and research to eventually quantify these effects.

The objectives of this study were (1) to characterize and define the information required from other CO₂ research programs and (2) to efficiently use this information, when it becomes available, to determine the information and research requirements within the fields in which indirect effects may occur.

This study is not an impact analysis and does not review methodology for impact studies. The Scope Report (Kates et al. 1985) is a good review of the state-of-the-art methodologies for doing impact assessment.

1.1 BACKGROUND

1.1.1 Atmospheric Carbon Dioxide

Carbon dioxide is a natural component of our atmosphere and is partially responsible for keeping the Earth at a temperature that supports life. Some of the radiation emitted from Earth (which would otherwise be transmitted to space) is absorbed or reradiated back to Earth by atmospheric CO₂. Carbon dioxide is also a nutrient for plants and is a by-product of the human metabolism, and is thus a usual component of the atmosphere in which we live. However, since the middle of the 1800s the concentration of CO₂ in the atmosphere has been increasing. This is principally due to the increased use of fossil fuels, but other human activities, such as clearing of forests, may also be contributing to the increase. For a number of years, this increase has been causing concern among scientists. It is predicted that, if the increase in atmospheric CO₂ continues, it may produce major global changes by (1) increasing global temperature with consequent changes in other climate variables and (2) changing the Earth's vegetation by affecting photosynthesis and water-use efficiency of plants. These changes may, in turn, result in other changes in the biosphere.

1.1.2 Definition of Indirect Effects

The continuing rise in the concentration of atmospheric CO₂ and the resultant changes in climate and vegetation may have global and regional effects, such as changes

in sea level; water availability; geographic patterns of agriculture, forests, and fisheries; and the prevalence of human disease. In the Department of Energy's Carbon Dioxide Research Program, these potential changes are termed the "indirect effects" of CO₂, so designated because they result from the "direct effects" of increasing CO₂, that is, climate change and vegetation response. The indirect effects may have substantial influence on human welfare; however, it is currently unknown whether collectively, and on a global basis, these effects will be beneficial or detrimental. Figure 1 schematically shows the relationship of atmospheric CO₂ to the direct and indirect effects of CO₂.

1.1.3 Interrelationships Between the Carbon Cycle and CO₂-Induced Direct and Indirect Effects

Figure 1 does not show the interactions and feedback that are a part of the CO₂ system.

The interactions of the various indirect effects with each other may modify the extent of the effects. That is, the full extent of the indirect effects cannot be predicted by looking at the effects on one field of study isolated from all others. Changes in water resources, for example, may affect (1) agriculture by changing the availability of water needed for plant life and growth, (2) fisheries by changing the timing and amount of terrestrial runoff into estuaries and bays, and (3) human health by changing the availability of water for drinking, cooking, and sanitation.

Indirect effects may also feed back to modify the direct effects of CO₂. Vegetation response due to increased atmospheric CO₂ may be modified by the effects of climate change on vegetation and vice versa; that is, the effects will be synergistic. Changes in vegetation may feed back to modify climate by changing the rate of evapotranspiration from plants, evaporation of moisture from soil, or by changing surface roughness or albedo.

The amount of CO₂ in the atmosphere may also be affected by CO₂-induced changes in vegetation. Growing plants take up CO₂ (sinks), and dead, decaying plants give off CO₂ (sources).

These examples of interactions and feedbacks point out that the various components of the CO₂ system and the CO₂-induced effects are highly interdependent and the whole system must be examined to predict the extent of the indirect effects of increased CO₂.

1.1.4 Status of Direct Effects Knowledge

Although direct effects research is being actively pursued and much information is evolving from this research,

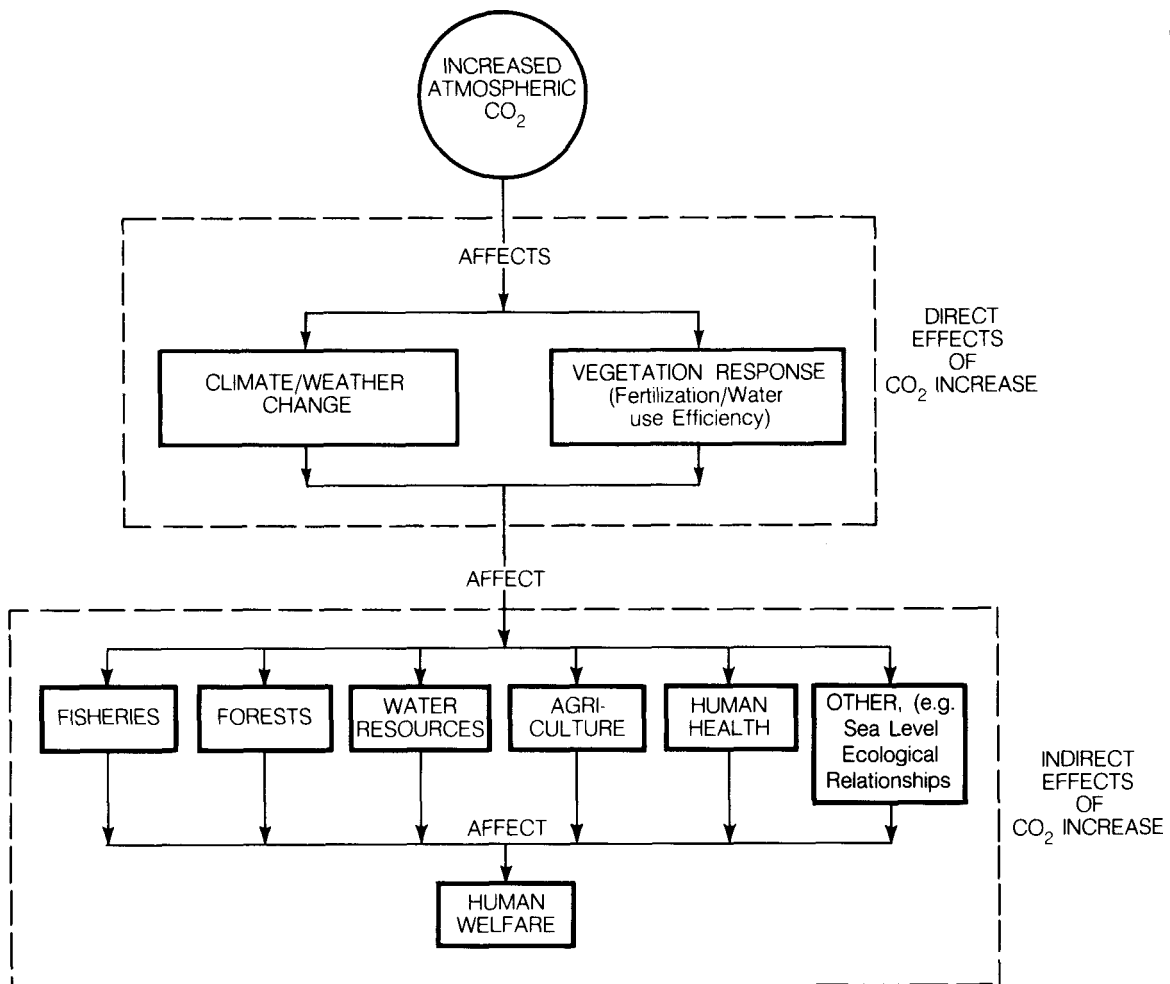


Figure 1.1. The sequence of events leading to the indirect effects of CO₂.

there are still many uncertainties in the information needed to quantify indirect effects. Chapter 2 of this volume presents a brief overview of the status of carbon dioxide research. More detailed information on the state-of-the-art research on the carbon cycle, climate change, and vegetation response is described, respectively, in Trabalka (1985); MacCracken and Luther (1985a, 1985b); and Strain and Cure (1985).

1.1.5 Previous Studies Related to Indirect Effects

The process for determining the consequences of increasing atmospheric CO₂ on human welfare must be an iterative process that will progress as information improves. A number of earlier studies have indicated the potential consequences of CO₂ increase and can be considered to be the first iteration of this process.

These reports and articles include Revelle and Suess (1957); The President's Science Advisory Committee Report (1965); National Academy of Science Report (1979); Elliot and Machta (1979); workshops supported by the Department of Energy and organized by the American Association for the Advancement of Science (American Association for the Advancement of Science 1980a, 1980b); The Council on Environmental Quality Report (1981); Brown et al. (1982). These reports, among others, point out the potential for effects of increased CO₂ that could affect human activities.

Scenarios of climate change, based on very tentative predictions of global change in temperature, were used to examine possible effects. Examples of these scenarios, which examined the relationship of climate change to agricultural productivity, water resource availability, fisheries, and forests are Benci et al. (1975), Ramirez et al. (1975), Stansel and Huke (1975), Stockton and

Bogges (1979), National Defense University (1980), Stewart (1980), Solomon et al. (1981), Revelle and Waggoner (1983). These and other scenarios were very useful because they (1) pointed to some of the potential effects of climate change, thus assisting in defining indirect effects study topics and (2) emphasized that these effects could have major impacts on human welfare and that CO₂ research should continue as a major priority.

Of necessity, these scenarios did not include many of the variables that may modify the effects of climate change, for example, the possibilities of (1) adaptation of crops to changed climate by genetic research, (2) climate effects modifying vegetation response and vice versa, and (3) vegetation change affecting water resources. In addition, the climate information on which they were based was extremely tentative because verifiable regional and seasonal information was not available. Thus, their value has been to support the urgency of research on CO₂.

1.2 APPROACH FOR THE CURRENT STUDY

The resources of the Earth are unevenly distributed among and within the continents and the oceans. For example, vast forests exist in North America but not in northern Africa. The drainage basins in the Eastern United States are very different from those in the Western United States. Many factors, including cultural and climatic differences, are responsible for the differences between agricultural practices in southeast Asia and those in South America. These regional distinctions define a fundamental prerequisite for determining the consequences of increasing atmospheric CO₂: climate change must be described on regional scales rather than as global averages. Current climate models predict changes in global average temperature but are not yet capable of reliably predicting regional and seasonal climate changes. Moreover, the areal dimensions of a region will differ depending on the effect, and the geographic area, being studied. Recognizing these conditions and the realities of available research resources and priorities, the studies reported here were of necessarily limited scope, with the following objectives:

- Based on information in the professional literature, select a limited number of key issues that seem likely to be affected by CO₂-induced climate and vegetation changes;
- Collect, analyze, and summarize what is generally known about the relationships between these issues and climate and vegetation;

- Identify data needs from the other CO₂ research programs (i.e., carbon cycle, climate change, and vegetation response) that are essential for determining the indirect effects of increasing CO₂;
- Identify, using case studies where appropriate, data and research needs related to the issues studied (including those that may be available from sources not yet identified in these studies) that are prerequisite to quantifying indirect effects when definitive regional climate change and vegetation response information become available.

Although the scope of these studies was limited, this did not limit the identification of many of the most critical data and research needs. However, due to time limits for preparing this report, in-depth examination of the full extent of the research necessary to supply these needs was not achieved. Entirely new research may have to be initiated in some instances, ongoing research may need to be reoriented or the methods revised, or needed information may be available but not yet located or properly organized and analyzed for the particular needs of CO₂ research.

1.3 THE CURRENT STUDY

The studies listed in Section 1.1.5 pointed to many of the potential effects of CO₂ increase and the urgency for continuing research on CO₂. However, the scenarios were limited because information necessary for conclusions was not available, as previously discussed. It was necessary, at this stage, to define the requirements that would enable research to go beyond scenarios—specifically, to define the information needed from carbon cycle, climate, and vegetation research and from fields in which the indirect effects occur. Also, it was necessary to determine which issues would be critically affected by the interaction of climate change and vegetation response and what external factors, such as technological advances and adaptive processes, would have the potential to influence the extent of the consequences of CO₂-induced effects.

The first step in the process of answering these questions was to select pertinent fields for study that were of critical importance to human welfare, that would cover many of the aspects of the indirect effects of CO₂, and that would lead to determining the major data and research needs for quantifying indirect effects. The fields selected, although not all-inclusive, were the ones emphasized in the earlier CO₂-related workshops and scenario studies as being important and responsive to CO₂-induced direct effects. These, coincidentally,

are also among the topics most frequently covered in the eight major climate impact studies, as tabulated by Maunder and Ausubel in the Scope report (Kates et al. 1985), and are among the topics most discussed in the National Research Council ([NRC] 1983) report, which was published after these topics were selected. The six topics selected for study were:

1. Sea Level
2. Water Resources
3. Agriculture
4. Fisheries
5. Forests
6. Human Health

Sea level has been studied and reported separately (NRC 1985). The reader is referred to that report for further information. Details about the relevance of the other topics to CO₂ effects will be found in Chapters 3–7; however, some of the reasons for their selection follow. Water resources and agriculture are vital for human survival and can potentially be affected by both climate change and vegetation response. Fishery catches are key to supplying nutrition (protein sources), particularly for many of the developing countries, and fisheries are very vulnerable to climate variables. In addition, fishery food chains may be important to the carbon cycle because they may affect the uptake of CO₂ by the oceans; that is, fishery food chains may convert the carbon of the CO₂, which dissolves in the oceans, to less reactive compounds, which may be precipitated and thus removed from the carbon cycle. Forests supply many products for societal use; they also have a large potential to be affected by both climate change and vegetation response and are intimately involved in the carbon cycle, taking up CO₂ (sinks) as they grow and releasing CO₂ (sources) as they and their products decay or are burned. Forests and fisheries also represent some aspects of the unmanaged ecology. There are also many aspects of human health that may be affected by climate change and vegetation response, and these effects may occur either as a direct consequence of climate change or, indirectly, through effects of climate change and vegetation response on agriculture, water resources, and fisheries.

Literature searches and, in some instances, case studies and models have been used to determine the relationships of climate and vegetation to these fields and to determine whether data or current research techniques are adequate for quantifying effects. From the information thus obtained, a first iteration of the data needed from the direct effects programs and of

the data and research needed within the fields studied has been determined. Some external factors, that may influence the consequences of the indirect effects, have been identified.

1.4 ORGANIZATION OF THE REPORT

Chapter 2 is a brief overview of the current status of research on the carbon cycle, climate change, and vegetation response. Chapters 3 through 7 discuss, respectively, the relationships of climate and vegetation parameters to water resources, agriculture, fisheries, forests, and human health. Each of these chapters then defines the data and research needs as currently perceived, for determining the indirect effects of CO₂. Chapter 8 summarizes the data needs from both CO₂ research and within the fields studied, and the research needed within the fields as they are perceived from the information collected for and described in Chapters 3 to 7 of this volume.

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2. BACKGROUND: CARBON CYCLE, CLIMATE, AND VEGETATION RESPONSES

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2.1 INTRODUCTION AND OVERVIEW

Rising levels of atmospheric carbon dioxide (CO_2) during this century and the next may have significant direct effects on climate and vegetation. This volume will investigate some of the possible impacts of the resulting changes in climate and vegetation on human health and welfare. This chapter will (1) briefly review the changes in atmospheric CO_2 that have occurred since 1850 and the projections for CO_2 increases in the future; (2) summarize the known historic and projected future climate changes in the context of increasing CO_2 and the means by which climate responses to CO_2 are studied; and (3) describe vegetation response in the context of climate changes and the global carbon cycle.

2.2 CARBON DIOXIDE LEVELS

There are four principal reservoirs, or regions of the Earth, through which carbon flows systematically: the atmosphere, the terrestrial biosphere, the oceans, and the geosphere, which includes the Earth's deposits of fossil fuels. Carbon can transfer between reservoirs through a variety of chemical, physical, geological, and biological processes. Reservoirs, or components of reservoirs, that release carbon to other reservoirs are termed sources, whereas those that take up carbon are termed sinks. The rate of carbon exchange between reservoirs is the carbon flux. This overall network of storage and transfer of carbon is known as the carbon cycle.

Human impact on the global carbon cycle is assumed to have been negligible before the latter half of the 19th century. Since then, the burning of fossil fuels and perhaps other anthropogenic activities such as deforestation have led to a significant increase of carbon in the atmosphere in the form of CO_2 . The burning of fossil fuel, for example, currently generates an amount of CO_2 equivalent to 5 gigatons ($10^{15} \text{ g} = 1 \text{ Gt}$) of carbon (Gt C) annually. This carbon represents a net transfer from the geosphere to the atmosphere relative to the natural exchanges of about 100 Gt C annually between the atmosphere and each of the remaining major carbon reservoirs (oceans and terrestrial biosphere). The result of this anthropogenic carbon flux superimposed on the natural exchanges of carbon has been a steady increase in the level of atmospheric CO_2 .

2.2.1 Historic Trends in Atmospheric CO_2 Concentrations

Measurements taken at the Mauna Loa Observatory in Hawaii have demonstrated that the atmospheric concentration of CO_2 has risen steadily over the last

quarter century (Figure 2.1). Concentration levels rose from 316 parts per million by volume (ppm) in 1958 to 326 ppm in 1970 and to 342 ppm in 1983, reflecting a roughly exponential trend. This trend is supported by an equally long, although discontinuous, record from the Antarctic (Keeling and Bacastow 1977) and by shorter records of various stations that have been incorporated into a global monitoring network (Machta 1983). The measured trend toward a higher concentration of atmospheric CO_2 over this period represents perhaps the best example of a "known" in the area of CO_2 research.

Measurements of CO_2 concentrations prior to 1958 are sporadic and of uncertain accuracy. However, it is possible through a variety of means to obtain modern estimates for that period. One approach is to estimate the ratio of atmospheric CO_2 increase to fossil fuel CO_2 input since 1958 (the "airborne fraction" of fossil fuel input), and then use this ratio to calculate pre-1958 levels of atmospheric CO_2 based on records of fossil fuel use. Other approaches are discussed in the *Atmospheric Carbon Dioxide and the Global Carbon Cycle* (Trabalka 1985) and include measurement of the CO_2 content of air bubbles trapped in polar and glacial ice (Neftel et al. 1985) and inference from ^{13}C data in tree rings (Stuiver et al. 1984).

Estimates of early 19th century (i.e., preindustrial) CO_2 levels derived through these methods range from 250 to 300 ppm. Machta (1983) used 250–295 ppm, but noted that a narrower range of 260–280 ppm was at that time considered by some experts to be the most likely values. The range of values selected in Chapter 3 of *Atmospheric Carbon Dioxide and the Global Carbon Cycle* is 260–285 ppm, though the range of best estimates is taken to be 275–285 ppm. These estimates therefore suggest an increase in CO_2 since

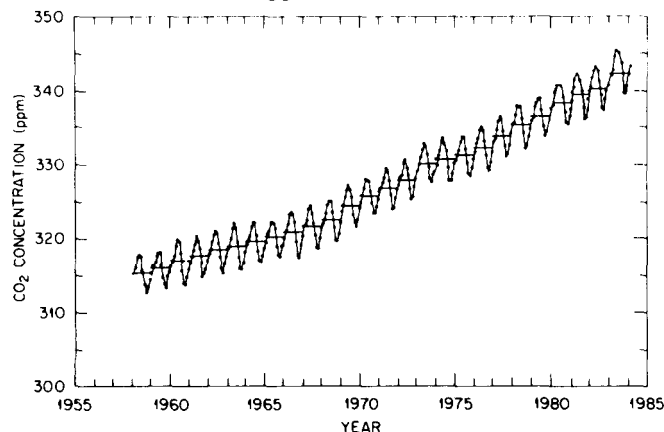


Figure 2.1. Concentration of atmospheric CO_2 at Mauna Loa Observatory, Hawaii, expressed as a mole fraction in parts per million of dry air. The dots depict monthly averages of visually selected data adjusted to the center of each month. The horizontal bars represent annual averages. Data were obtained by C. D. Keeling, Scripps Institution of Oceanography, University of California, La Jolla, California.

1800 of about 22% (calculated using values of 280 ppm for 1800 and 342 ppm for 1983). Estimates of greater than 290 ppm for preindustrial times were obtained by backward extrapolations based on fossil fuel input and by assuming that the other carbon fluxes and exchanges are constant. The lower estimates discussed above have been obtained by other estimating techniques, and these lower estimates imply that a nonfossil source of variations in the fluxes between the atmosphere and the other reservoirs (oceans and terrestrial biosphere) has also contributed appreciably to changes in atmospheric CO₂ concentrations over the last century.

2.2.2 Future Trends in Atmospheric CO₂ Concentrations

Edmonds et al. (1984) have projected several CO₂ trends, each based on a different set of assumptions and scenarios. These projections, all of which are consistent with the current state of knowledge, are shown in Figure 2.2. There is some consensus that a value of 400 ppm will be reached early in the 21st century, but beyond the year 2020 the various projections diverge appreciably. The high-fossil-fuel-emissions projections in Figure 2.2 indicate that 600 ppm (approximately twice the value estimated for the beginning of this century) will be attained by 2040, whereas the more conservative projections indicate that such levels will not occur before 2075. These curves are useful indicators of the considerable range of possible future trends in atmospheric CO₂ concentration. However, the complexities of the carbon cycle (see Trabalka 1985) make simplistic exponential growth rates unlikely, especially for time periods of over a century.

Future trends in energy use are important unknowns affecting the above projections of future concentrations of atmospheric CO₂. Other uncertainties include non-fossil terrestrial CO₂ sources and sinks and the role of the oceans. Information on the historic behavior of various components of the carbon cycle can contribute much to reducing these uncertainties as such information becomes available and is shown to be reliable. More details about projections of future atmospheric CO₂ concentrations are given in Edmonds et al. (1984) and Trabalka (1985).

2.3 EFFECTS OF CO₂ ON WEATHER AND CLIMATE

Weather may be thought of as the complete state or behavior of the atmosphere at a particular moment of time and the evolution of this state in terms of individual atmospheric disturbances. Climate is the synthesis

of weather over a period long enough to establish its statistical properties and is largely independent of any instantaneous weather state (World Meteorological Organization [WMO] 1979). The climate of a given region is determined by a complex set of forces and influences, often involving inhibiting, reinforcing, or self-perpetuating feedbacks that occur between the atmosphere and other components of the climate system including the land surface and terrestrial biosphere, the world's oceans and freshwater systems, and the world's masses of ice and snow.

Climate change may thus be described as a change in the generalized weather, or in the general patterns of

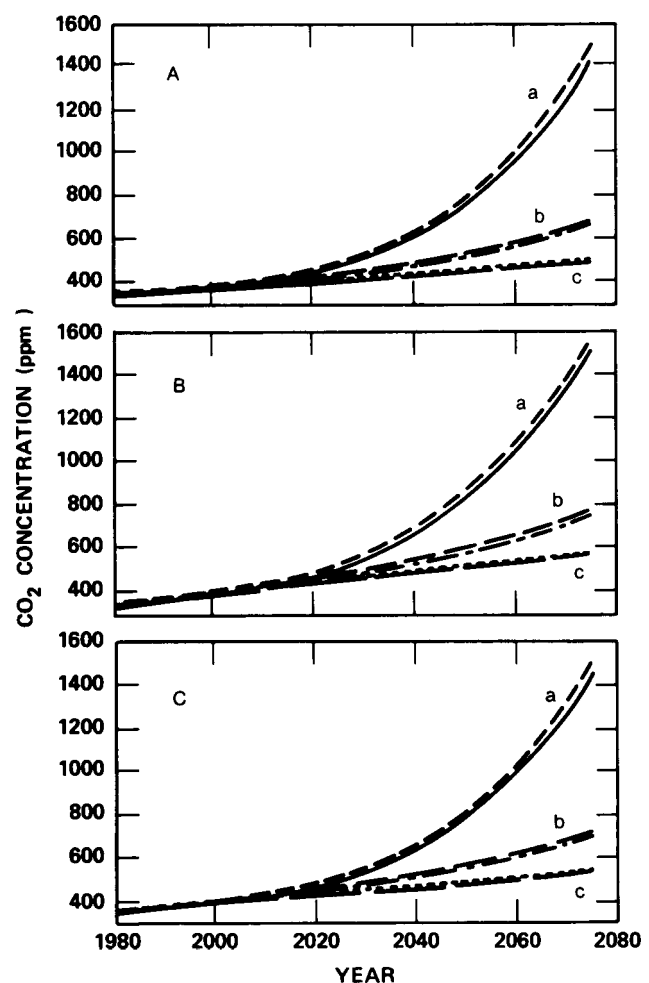


Figure 2.2. Range of projections of atmospheric CO₂ concentration. (A), (B), and (C) are projections based on different assumptions about the role of the terrestrial biosphere in determining past values of atmospheric CO₂ concentration. Curves within each frame represent high (a), standard (b), and low (c) scenarios for future fossil-fuel emissions. Source: Trabalka (Chapter 10) (1985).

weather, and it is understood that such changes would be accompanied, either as cause or effect, by changes in other components of the climate system. Given that the interacting components of the climate system and the effects of climate changes on human health and welfare all vary over a wide range of temporal and spatial scales, attempts to illustrate potential impacts of climate change must describe climate in terms of generalized weather for particular regions and seasons. The rate of climate change is also important because slow changes allow time for adaptations and are, therefore, less likely to be highly disruptive.

2.3.1 CO₂ and Global Warming

The ability of the Earth and its atmosphere to absorb and reradiate heat is a critical factor influencing climate. CO₂ and other radiatively important gases, including water vapor, reduce the rate of loss to space of energy from the Earth's surface and lower troposphere. The effect is to increase the surface air temperature more than 30°C above the temperature the Earth's surface would have if there were no atmosphere. The effect is in some (limited) ways analogous to that created by a greenhouse, and consequently it is termed the "greenhouse" effect. The trend toward an increased concentration of atmospheric CO₂ implies that its radiative influence will also increase, leading to increases in the surface air temperatures.

This possibility has been studied by various scientists for over a century. Manabe (1983) traces the progression of scientific thought on this subject from Tyndall (1863) to Möller (1963) before summarizing the more sophisticated approaches to the problem that have been attempted over the last 20 years.

2.3.2 Empirical Studies of Past Climate Changes

The available temperature records, summarized by Wigley et al. (1985), and shown in Figure 2.3, indicate a general warming in the Northern Hemisphere during the last hundred years. Although this increase coincides with the previously discussed increase in atmospheric CO₂ concentration since the mid- to late-19th century, these data cannot confirm the hypothesis of CO₂-induced warming for two important reasons. First, it is highly uncertain whether variations in solar activity, atmospheric turbidity (e.g., volcanic eruptions), or unknown causes of climate variability have been properly accounted for in explaining the temperature record. Second, the temperature record itself is of questionable validity. It is based on observations made almost entirely in the Northern Hemisphere and

contains few measurements made over the oceans. However, as noted by the National Research Council ([NRC] 1983, p. 34), the temperature data do not preclude the possibility that slow climate changes caused by CO₂ may already be under way. This idea has led to much effort in "first detection" of a climate effect, or effects, that could be defensibly attributed to increasing atmospheric CO₂ concentration (U.S. DOE 1983, Chapter 5). Such studies are beyond the scope of this chapter, but are discussed more fully in *Detecting the Climatic Effects of Increasing Carbon Dioxide* (MacCracken and Luther 1985a), and in Chapter 5 of the recent NRC (1983) report.

Empirical studies of past climate data can also serve to identify authentic regional patterns of climate change that may occur in the context of a global-scale warming of a few tenths of a degree Centigrade. For

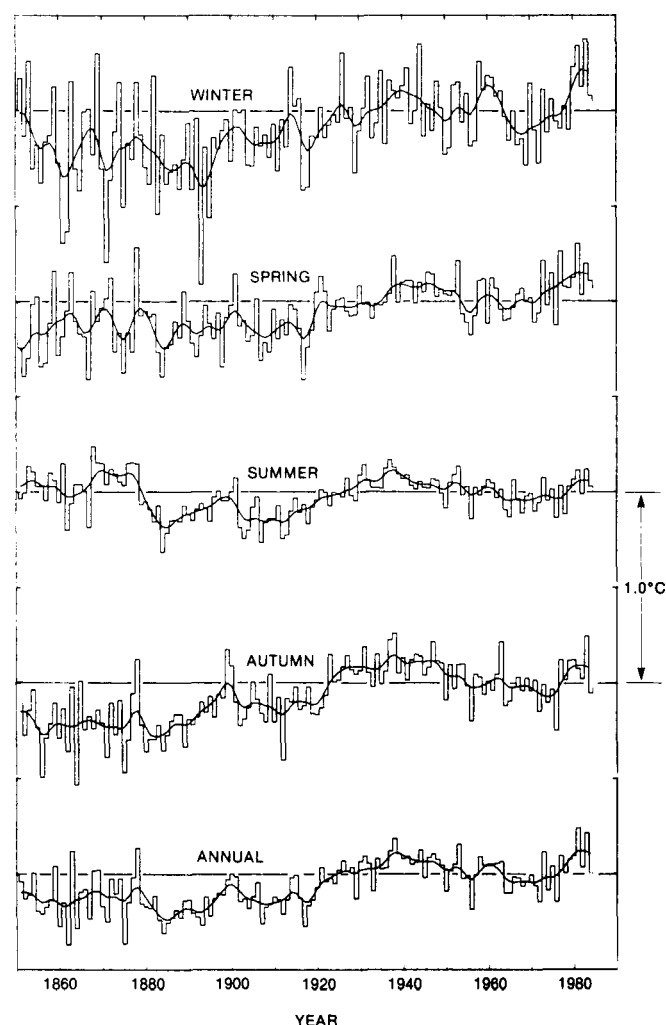


Figure 2.3. Estimated seasonal and annual mean Northern Hemisphere surface air temperatures, expressed as departures from the 1946–1960 mean. Source: Wigley et al. (1985).

example, Lough et al. (1983) and Palutikof et al. (1984) have depicted patterns of differences in temperature, precipitation, and pressure between warm and cool periods in the 20th century. However, the geographic limitations of data coverage preclude empirical studies of climate change in many regions. In addition, these data sets only describe relatively recent periods when the Northern Hemisphere average surface air temperature was within 0.5°C of the present value and never more than 0.1°C above the present. The possible climate responses of a significant global-scale warming caused by increased CO₂ are by no means limited to those experienced over the last century. Nonetheless, empirical illustrations comparing warm years with cold years may be useful in suggesting realistic regional patterns of seasonal climate change corresponding to the slight warming that could occur on the time scale of the next decade.

2.3.3 Climate Modeling

In the absence of a sufficient range of empirical data, computerized simulation models of the atmosphere, based on physical principles, have emerged as a possible means of estimating climatic effects of increased atmospheric CO₂. These models exist at varying levels of complexity, ranging from simple one-dimensional, radiative-convective models to three-dimensional general circulation models so termed because they simulate many of the complex processes involved in the general circulation of the atmosphere and in its interaction with other components of the climate system. These models, and other aspects of climate research, are discussed in *Projecting the Climatic Effects of Increasing Carbon Dioxide* (MacCracken and Luther 1985b).

Surface air temperature statistics of these models are usually calculated for a doubling or quadrupling of atmospheric CO₂. This is so because climate modelers generally have found it necessary to simulate such large increases to distinguish the effects of CO₂ (the CO₂ "signal") on climate from the background variability (noise) associated with climate. The sensitivity of global average surface air temperature to increased CO₂ concentrations is broadly consistent for different models regardless of complexity. In summarizing the consensus of these simulation results, NRC (1983) estimated the equilibrium global surface warming for a doubling of CO₂ to be between 1.5° and 4.5°C. This range of estimates is also found in earlier studies by the NRC (1979, 1982). The warming is expected to be greatest in polar regions—about two to three times greater than in the tropics (NRC 1982, 1983).

Although all of the models project a global average warming, they vary significantly in their abilities to achieve regional resolution. To estimate the effects of a climate change, the climate change must be projected in terms of its geographical diversity and temporal variability. The only models that can simulate climate in such detail are those that simulate the large-scale circulation features of the atmosphere such as the high- and low-pressure systems that characterize a typical weather map. Models that simulate the general circulation of the atmosphere and its attendant weather features are known as general circulation models, or GCMs.

State-of-the-art GCMs were not intended for use in climate-impact studies, but rather were designed to aid in learning about the causes and nature of climate via attempts to simulate climate. In fact, these models are objective, quantitative characterizations of the state of knowledge about climate, and shortcomings in that knowledge will manifest as shortcomings in the model simulations. Identification and characterization of these shortcomings can aid in learning about why they occur and thus aid in acquiring knowledge about climate.

The level of spatial resolution of GCM simulations is determined by the grid scale of the model—that is, the distance between points at which the model computes the simulated values of an ensemble of climate variables. In current GCMs, the distance between any two gridpoints is typically about 500 km. The spatial resolution is limited by the amount of computer time required to solve the complexes of equations at large numbers of gridpoints. The nature of these equations and the nature of the physical processes the equations represent require that they be solved at rather short simulated time intervals. At the current level of spatial resolution, the weather must be simulated at intervals of about 10 minutes, and the statistics of these weather simulations are then calculated to characterize the simulated climate.

The spatial resolution of current GCMs is sufficient to characterize features of the large-scale atmospheric circulation (e.g., movements of warm and cold air masses) but cannot characterize precipitation, which has a smaller spatial scale and a more heterogeneous geographic distribution than that of temperature. Consequently, precipitation must be treated statistically, rather than treated as a physical process, causing simulations of precipitation to be especially questionable for use in regional impact studies. For this and other reasons (e.g., problems with modeling soil moisture fluxes), hydrologic variables, although among the most important variables for many impact studies, are among the most poorly simulated by climate models.

A summary and intercomparison of the simulations of CO₂-doubled climate, produced by different GCMs, has been presented by Schlesinger and Mitchell (1985). There is some general consensus that warming will be greatest at high latitudes, but there are still appreciable model-to-model differences in the geographic distribution of the simulated temperature changes (Figures 2.4 and 2.5). For reasons given above, there is even more model-to-model variability in the geographical

distribution of simulated precipitation, as seen in Figures 2.6 and 2.7.

Another important characteristic of GCMs that detracts from their use in the determination of indirect effects of CO₂-induced climate changes is that the models are so computationally demanding they can only simulate a few years of climate. The most complex GCMs are conventionally used to simulate only the climatic state that is in equilibrium with a doubled,

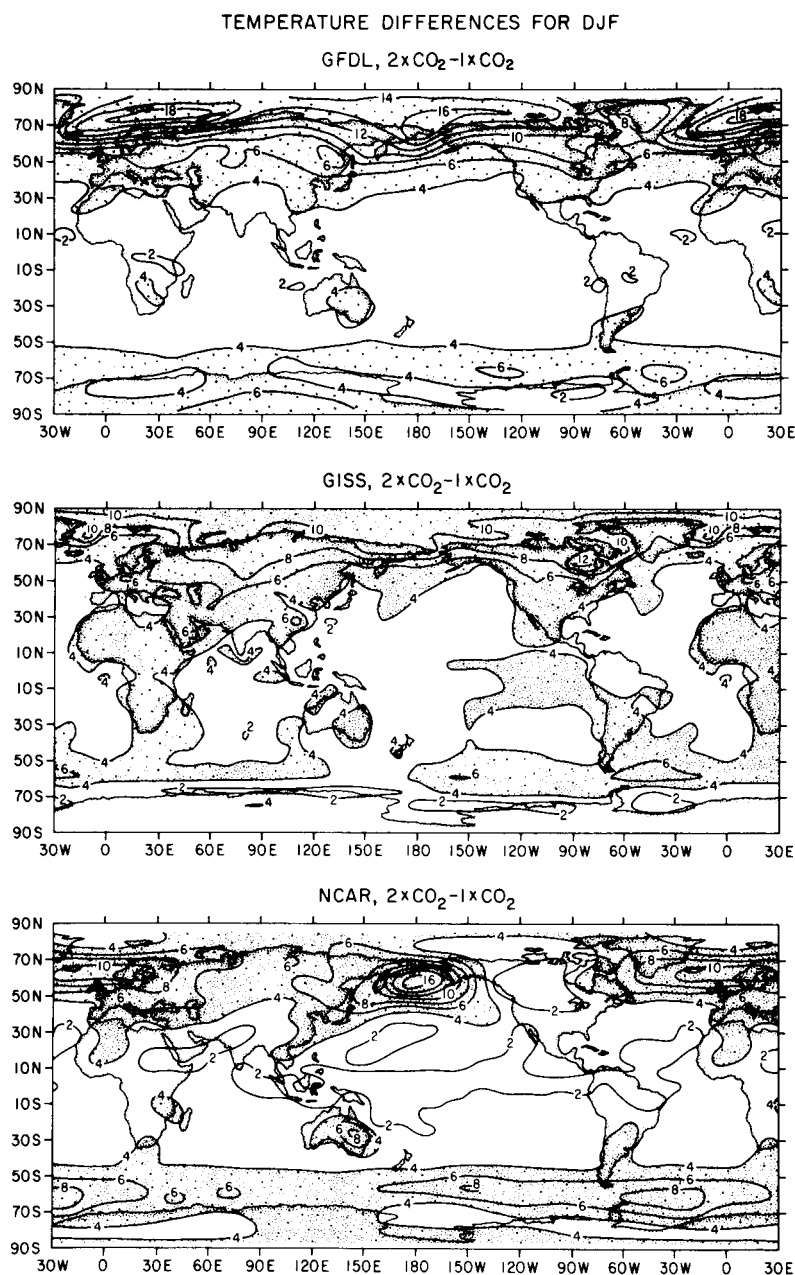


Figure 2.4. Geographical distribution of the surface-air temperature change (°C) in winter (December [D], January [J], February [F]) for a CO₂ doubling, as simulated by three general circulation models. The Geophysical Fluid Dynamics Laboratory (GFDL) simulation (top) is described by Wetherald and Manabe (in press), the Goddard Institute for Space Studies (GISS) simulation (middle) is described by Hansen et al. (1984), and the National Center for Atmospheric Research (NCAR) simulation (bottom) is discussed by Washington and Meehl (1984). Source: Schlesinger and Mitchell (1985).

or quadrupled, amount of CO_2 . The relatively long process of achieving equilibrium is not treated by these models. Simpler models can be used to study the transient or time-dependent features of the evolving climate state, but those models only incorporate the levels of spatial resolution and complexity required to treat a highly idealized and simplified climate system.

Also, the most complex GCMs do not yet completely incorporate oceanic responses to CO_2 increases and the resultant interactions with climate, although appreciable progress is being made in that area.

In summary, model simulations do not currently provide information on several aspects of climate that are important to the evaluation of indirect effects

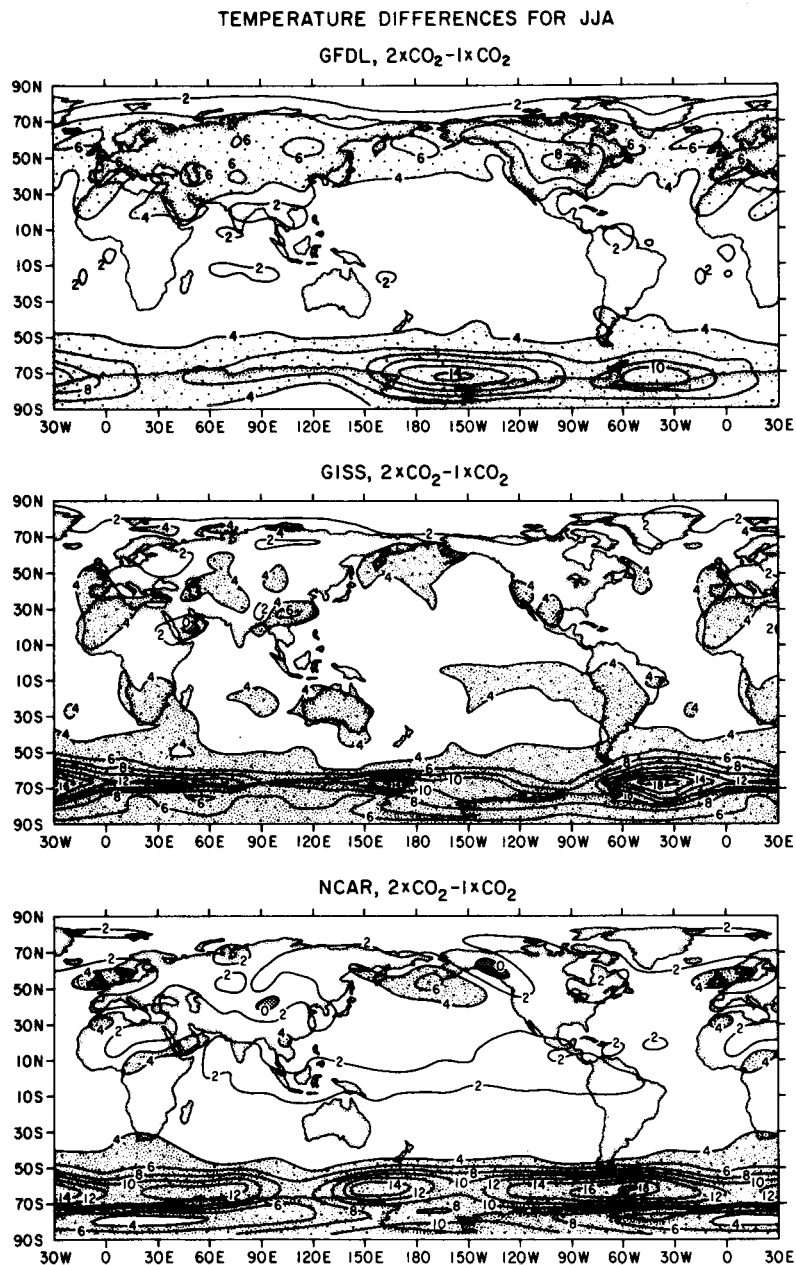


Figure 2.5. Same as Figure 2.4 for summer. (June [J], July [J], August [A]). Source: Schlesinger and Mitchell (1985).

of CO₂-induced climate changes in particular regions. These unknown aspects of climate change often fall into one or more of the following overlapping categories:

1. Transient or time-dependent phases of climate change;
2. Processes on smaller scales than the spacing between points on the computational grid network of the model (about 500 km);

3. Regional and seasonal components of climate; and
4. Ocean-atmosphere interactions and ocean-temperature changes.

This state of the art in climate modeling precludes predictions of climate change or its impacts on particular regions. However, it is still possible to use the GCM simulations as illustrations of credible possibilities that

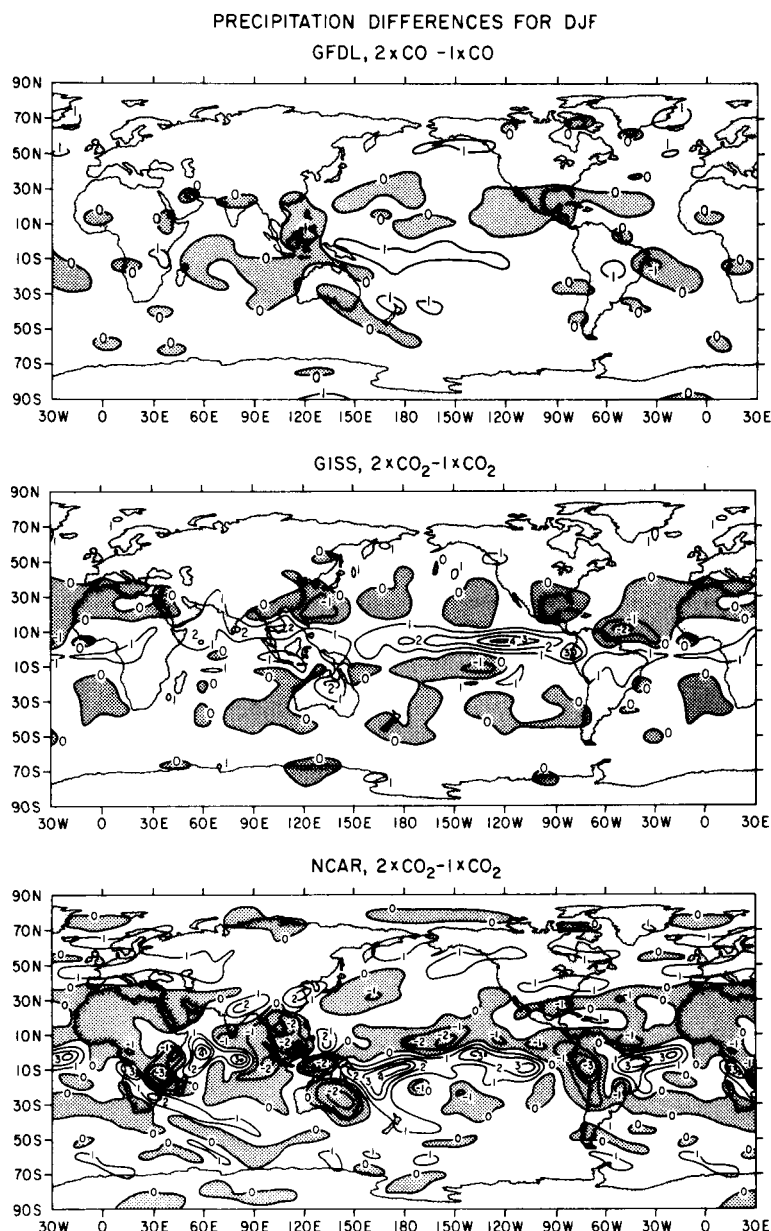


Figure 2.6. Same as Figure 2.4 for winter precipitation. Source: Schlesinger and Mitchell (1985).

are consistent with current knowledge of atmospheric behavior, as suggested in a recent report of the NRC (1983, p. 275):

While present models are not sufficiently realistic to provide reliable predictions in the detail desired for assessment of most impacts, they can still suggest scales and ranges of temporal and spatial variations that can be incorporated into scenarios of possible climatic change.

From these illustrations it is possible to investigate the sensitivity of certain systems (e.g., agricultural systems, forest ecosystems) to a plausible range of

climate changes. As with climate models themselves, the current objective of climate impact scenarios is to learn about the systems involved because prediction is not a state-of-the-art capability. Case studies of potential indirect effects have helped to specify the information that is still needed from various disciplines to reduce uncertainty in anticipating the consequences of increasing CO_2 . Specific illustrations of possible indirect effects of climate change are given in some of the following chapters of this volume. The climate scenarios used are consistent with GCM simulations and with empirical relationships between temperature

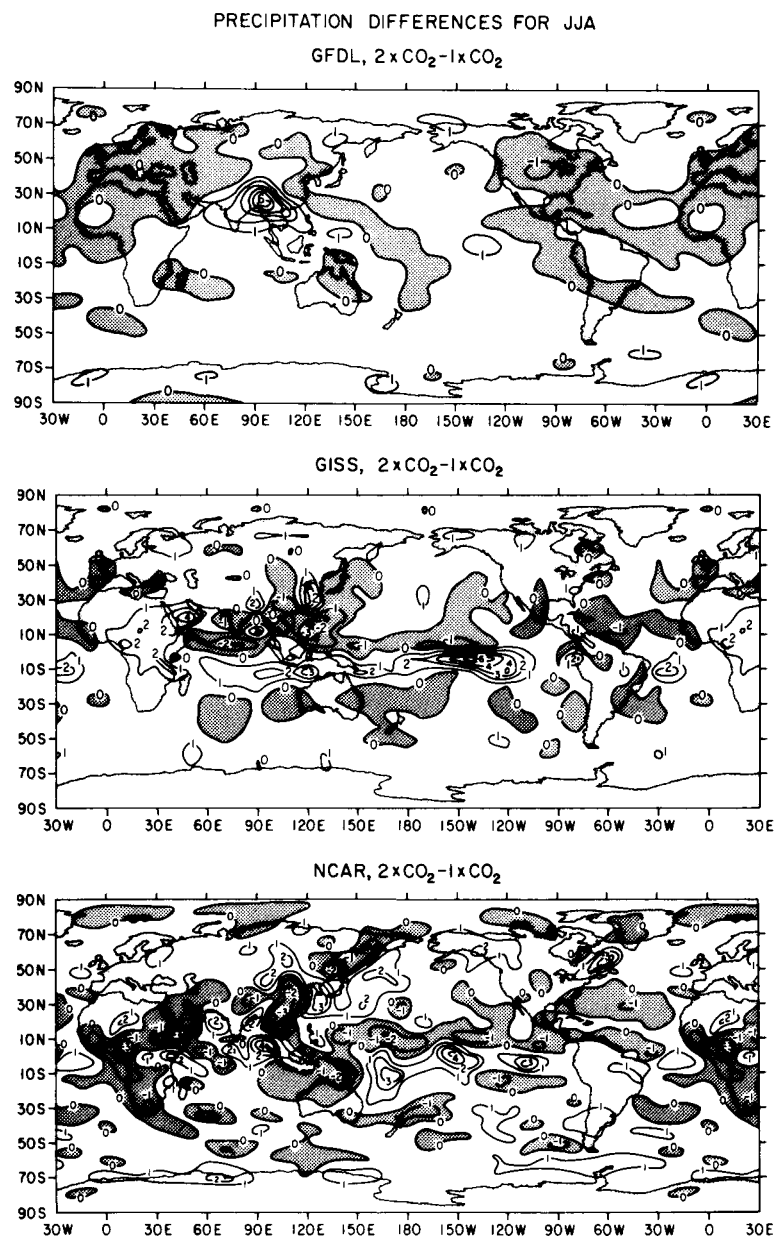


Figure 2.7. Same as Figure 2.4 for summer precipitation. Source: Schlesinger and Mitchell (1985).

and precipitation. In this context, the different climate input scenarios used for the various regions of study are consistent with each other.

2.4 VEGETATION RESPONSES TO INCREASED CO₂

If all other factors are held constant, increased atmospheric CO₂ is likely to benefit most plants. This is so because the major direct effects of increased CO₂ on plants are thought to be increased photosynthesis and decreased transpiration (Strain and Cure 1985). Increased photosynthesis would favor increased plant growth as long as nutrients, soil moisture, or other factors do not limit growth. Decreased transpiration is related to the effect CO₂ has in reducing the size of the stomata (small openings in the epidermal tissues of the leaves), resulting in decreased water loss by transpiration. This effect is expected to at least partially offset the effects of increased drought that may occur in some regions via CO₂-induced climate change. However, the positive implications of these aspects of rising atmospheric CO₂ may be reversed, cancelled, reduced, or enhanced by two factors: differential plant-species responses to CO₂ and climate changes associated with increased CO₂.

Some classes of plants are expected to benefit more than others from the direct vegetative effects of increased CO₂. In some agricultural systems, economically undesirable plants (weeds) could benefit more than crops. In forests, the long time scales over which individual trees compete with each other may lead to a wide variety of outcomes. For example, changes in the species composition of forests in one region may benefit the lumber industry but not the pulp and paper industry, whereas the opposite may be true in another region. In other cases, industry may be little affected after some strategic adjustments.

Nutrient stress further complicates the assessment of differential response. In forests, where soil nutrients are not typically controlled by application of fertilizers, the direct effects of CO₂ increases may be limited from species to species by the inability to obtain necessary nutrients.

Although CO₂ increases are likely to be relatively constant from one region to the next, the associated climate changes will be spatially heterogeneous and consist of the integrated effects (sometimes opposing effects) of a myriad of variables (e.g., temperature, humidity, windspeed, precipitation). The interaction of climate change with direct vegetative effects of CO₂ further expands the number of possible vegetative responses, including beneficial and detrimental outcomes.

Increased photosynthesis resulting from increased CO₂ may benefit some aquatic plant species, whereas effects on transpiration (for emergent aquatic species) would seem less important than they are to land species. The influence of climate will be complicated by the geographic diversity of climate change and by the effects of climate change on the ocean currents, which influence water temperature and nutrient supply.

Thus, details of how differential plant-species responses and interactions of climate change with direct vegetative effects may affect forests, agricultural systems, or aquatic ecosystems are as yet unknown (Strain and Cure 1985).

Response times are also uncertain. The long life span of trees implies that forests may take as much as two to three centuries to adjust to an appreciable climate change. Therefore, in Chapter 6 of this volume, Solomon and West discuss the approach of using a forest-succession model to simulate the time-dependent response of forests in eastern North America to a CO₂-induced climate change. Because current GCMs do not simulate the time-dependent response of climate to increasing atmospheric CO₂, linear interpolations between present climate conditions and simulated equilibrium climates for a CO₂ doubling and quadrupling are used as inputs to the forest succession model. The representations of climate for a CO₂ doubling and quadrupling are taken to be generally consistent with several GCM simulations, as discussed in an earlier report by Solomon et al. (1984).

Although the discussion above concerns the impact of atmospheric CO₂ on vegetation, it is important to note that vegetation response may partially counteract rising levels of atmospheric CO₂ and consequent climate effects. Forests, for example, are an important component of the global carbon cycle, and the globally integrated effects of atmospheric CO₂ increases may lead to changes in the amount of carbon stored in the world's forests. If only direct vegetative effects (increased photosynthesis and decreased transpiration) are considered, the net effect is likely to be an increase in carbon stored in forests, although this effect will probably be partially offset by increased respiration. The geographic distribution and seasonal timing of CO₂-induced climate changes will also influence this aspect of the carbon budget (Trabalka 1985). Thus, even the direction of future changes in total carbon stored in the world's forests is not certain.

2.5 SUMMARY

This chapter provides a brief background on various aspects of CO₂ research pertinent to understanding the findings regarding the indirect effects of rising

atmospheric CO₂ on human health and welfare that are presented in this volume. This overview includes discussions on historic and projected increases in atmospheric CO₂ concentration, the significance of these increases in terms of world climate, evidence of recent and ongoing climate changes, efforts to anticipate future climate changes, and the potential response of vegetation to higher levels of CO₂. Table 2.1 summarizes some of the more important reference data contained in this chapter.

Clearly, there is much uncertainty regarding the relative influence of each of the several direct climatic

and vegetative effects in producing the conditions that will lead to the various indirect effects. Rising levels of CO₂ over the last quarter century are well documented, and it is generally accepted that a doubling of CO₂ concentration from that prevailing at the beginning of the 20th century will cause appreciable warming of the lower troposphere. However, the point in the future at which a doubling will be reached, the impact of the doubling on climate at a regional level, the nature of the tradeoffs between increased photosynthesis and climate change on plant productivity, and numerous other factors are subject to much uncertainty.

Table 2.1
Summary of Reference Data Pertaining to Indirect Effects

Subject	Data
Carbon Cycle	
CO ₂ Levels for the year 1800	260–285 ppm
Recent CO ₂ levels: Year 1958	316 ppm
Year 1970	326 ppm
Year 1983	342 ppm
Percentage increase in CO ₂ since 1800 (using 280 ppm for 1800 and 342 ppm for 1983)	22%
Reference level for CO ₂	300 ppm (approximate value for year 1900)
“Doubling” level for CO ₂	600 ppm
Projected year of “doubling”	Wide range of estimates
Rapid-increase projections	Year 2035 to year 2040
Slow-increase projections	Year 2075 and beyond
Climate and First Detection	
Temperature increase from 1850 to present	Less than +0.5°C (not necessarily due to CO ₂)
Projected temperature increase from present to point of “doubling”	+1.5°C to +4.5°C
Projected regional distribution of warming	Uncertain; greatest in polar regions
Projected precipitation change from present to point of “doubling”	Regionally variable; uncertain for specific regions
Vegetative Response to CO₂	
Photosynthesis	Positive response
Transpiration	Decrease (positive response)
Benefits to economic vs. uneconomic plants	Uncertain
Net ecosystem production (carbon storage)	Uncertain
Response time of vegetation	Uncertain; depends on life span of plants and rate of CO ₂ increase
Regional responses	Highly uncertain; depends on regional responses of climate

Thus, the reader is reminded that the scenarios to follow are only illustrations of realistic possibilities and are not predictions or projections. They are, however, valuable in that they constitute careful exercises in logical thought based on the best available knowledge, and they allow for the investigation of the sensitivity of various systems to a plausible range of climate changes. The actual ability to predict indirect impacts is, of course, ultimately dependent on the continuing progress in empirical studies and modeling.

ACKNOWLEDGMENTS

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3. WATER RESOURCE SYSTEMS AND CHANGES IN CLIMATE AND VEGETATION

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3.1 INTRODUCTION: CO₂, WATER RESOURCES, AND SOCIETY

Scientists predict that the ambient concentration of carbon dioxide (CO₂) in the Earth's atmosphere could reach 600 parts per million by volume (ppm) by the middle of the next century (National Research Council [NRC] 1983). As this happens, the Earth's surface is expected to become warmer. Global warming is also expected to increase the intensity of the global hydrologic cycle (MacCracken and Luther 1985). The effect of changes in the ambient concentration of CO₂ on the world climate system is only partially understood at this time. However, results obtained from global circulation models (GCMs) (Manabe and Wetherald 1980; Washington et al. 1980; Manabe et al. 1981; Wetherald and Manabe 1981; Washington and Meehl 1982) suggest that changes in global mean temperature and precipitation will not be uniformly distributed spatially or seasonally.

An increase in atmospheric CO₂ to 600 ppm could enhance the growth and productivity of many different plant and tree species and reduce the amount of water required to sustain incremental changes in plant biomass (Strain and Cure 1985). These physiological effects of CO₂ buildup may, in turn, influence competition, succession, selection, and ultimately the composition of natural ecosystems. These effects could also influence the relative profitability of commercially important crop species, leading to changes in the pattern of spatial differentiation in crop production worldwide (Wittwer 1980).

Precipitation and temperature patterns, soil moisture requirements, and the physical structure of the vegetation canopy play important roles in the hydrologic system of drainage basins. Changes in these phenomena, because of a buildup of CO₂, have the potential to affect the quantity, quality, timing, and spatial distribution of water available in a basin to satisfy the many demands placed on the resource by society. In addition the location, timing, and magnitude of many different types of demand for water may be quite sensitive to the effects of CO₂ buildup on temperature and vegetation. This may be true of the demand for water used to irrigate crops, to generate electricity, for heating, ventilation, and cooling (HVAC) systems, and for drinking and sanitation—all of which are sensitive to variations in temperature or precipitation. Consequently, it is important to focus research on both the effects of changes in climate on natural water resource systems and the interaction between humans and their environment.

This chapter aims (1) to identify, characterize, and define the probable scope of the indirect effects, both detrimental and beneficial, of increasing atmospheric

CO₂ concentrations on relevant water resource issues, and (2) to identify specific information regarding climate effects and the vegetation response required to further advance research on the indirect effects of CO₂ buildup on global water resources.

This chapter is organized into seven major sections. Section 3.2 identifies major physical linkages between climate, vegetation, and the hydrologic system useful for characterizing the potential impacts of CO₂ buildup on water resource systems. Section 3.3 identifies the global water resource issues selected for analysis and the subset of generic issues judged to have the highest probability of being affected by CO₂ buildup. This section contains a more detailed discussion of the potential effects of CO₂ buildup on these generic issues. Section 3.4 describes the procedures used to select a case study site for examining the indirect effects of CO₂ buildup on these generic issues and summarizes the results of this investigation. Section 3.5 summarizes the knowns, unknowns, and uncertainties about the potential effects of CO₂ buildup on water resource systems. Finally, Section 3.6 identifies information and future research required to resolve the unknowns and reduce the uncertainties identified in Section 3.5.

3.2 INTERACTIONS AMONG CLIMATE, VEGETATION, AND THE HYDROLOGIC SYSTEM

Water resource issues arise when the services provided by the hydrologic system of a drainage basin are no longer consistent with the needs of water users. CO₂ buildup can influence water resource systems through its effects on principal state variables within the hydrologic system, such as temperature, soil moisture, and snow mass and on the primary energy and moisture fluxes that influence or are produced by these state variables. This section of the chapter identifies the relevant linkages between climate, vegetation, and the hydrologic system that may be influenced by CO₂ buildup.

3.2.1 The Hydrologic Balance

The hydrologic system of a drainage basin is a dynamic entity consisting of three basic components: (1) the medium acted upon (water in its various physical states); (2) a set of constraints applied by the physical nature of the watershed; and (3) the driving forces of direct solar energy, gravity, and capillary potential fields (Eagleson 1978, 1982). The component processes of the hydrologic system are interrelated by the continuity of mass as described by the equation of hydrologic equilibrium (Todd 1964):

$\text{Inflows} + \text{Precipitation} + \text{Storage Increases} = \text{Outflows} + \text{Evapotranspiration} + \text{Storage Decreases} + \text{Consumption}.$

Figure 3.1 is a graphic representation of the continuity of mass for the hydrologic system of a drainage basin. In the diagram precipitation enters the system from clouds in the form of rain or snow. A portion

of this precipitation is intercepted by trees, plants, and manmade structures from which it is evaporated. The remaining precipitation, or throughfall, reaches the land surface either as rainfall or snow. The rainfall that reaches the land surface may be temporarily stored in depressions and gullies. From there, this moisture can take one of three paths: it can be evaporated

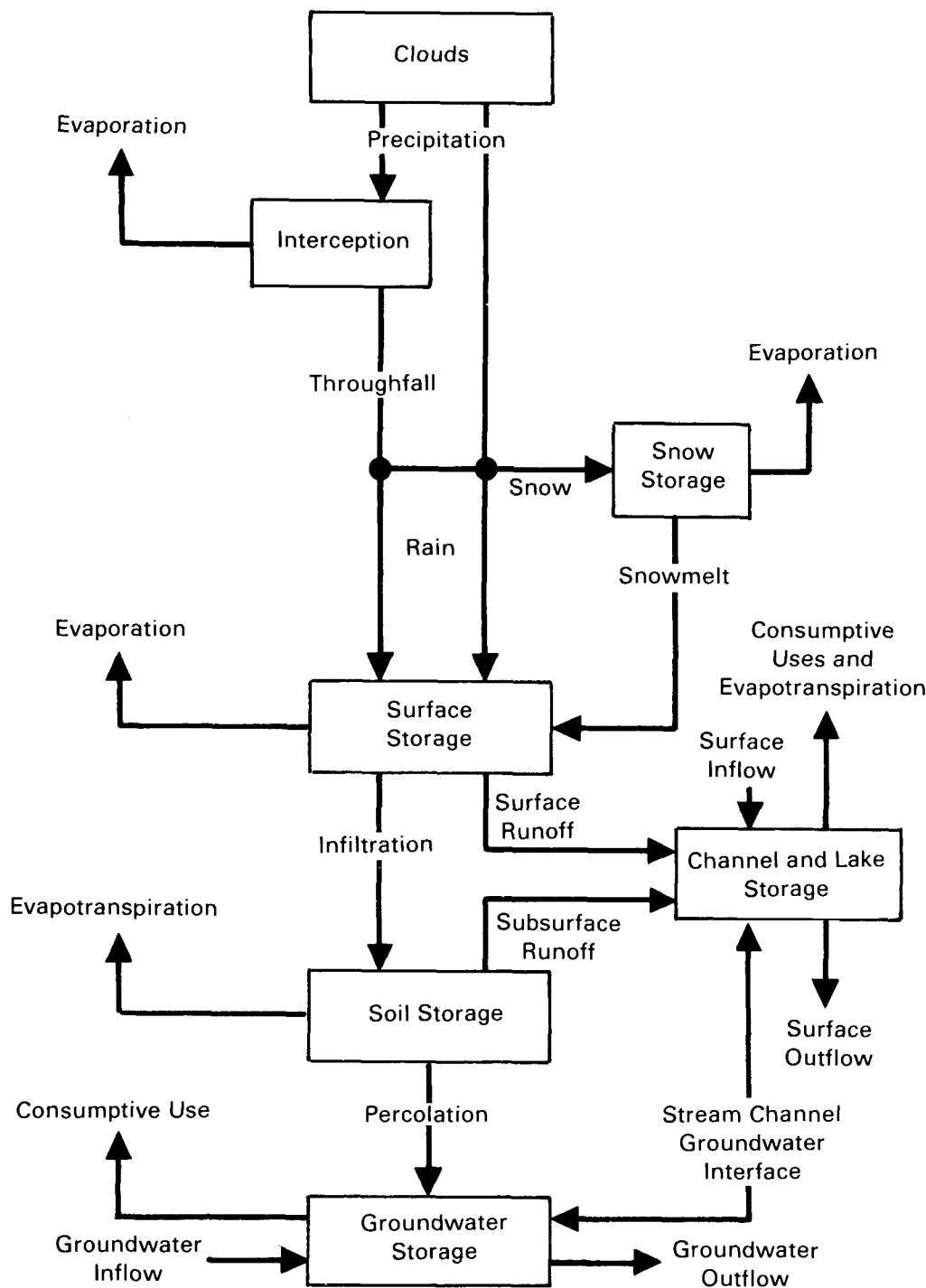


Figure 3.1. Schematic diagram of the hydrologic system of a drainage basin.

into the atmosphere, it can be carried to streams in the form of surface runoff, or it can infiltrate the soil. Snowfall, on the other hand, is usually stored for a period of time. The portion of snowpack that does not evaporate (or does not permanently remain in storage) eventually melts and follows the same paths as does rainfall, albeit with time lags. Water stored in soil can be evaporated directly into the atmosphere or it can be taken up by plants and turned into water vapor through the process of evapotranspiration. The remaining soil moisture either flows into lakes and streams as subsurface runoff (sometimes known as interflow) or percolates into groundwater storage. In many watersheds, the groundwater and stream channel storage systems are physically joined. Whenever this is the case, streamflow recharges the groundwater system through channel seepage during periods of peak runoff. During the dry season, on the other hand, streamflow may consist entirely of base flow, which is groundwater moving into the stream channel. Finally, Figure 3.1 shows that lakes, streams, and groundwater storage can be depleted by man (consumptive uses) or evapotranspiration and that all of these storage systems are subject to changes in mass caused by inflows from and outflows to other drainage basins.

The continuity of mass in Figure 3.1 represents an accounting system that can be used to describe the movement of water in its different states through the hydrologic system at specific points in time and space. However, the water balance shown above is insufficient by itself, even as a purely conceptual tool, for identifying the effects of climate change on water resource systems. To do this at any level of abstraction requires an understanding of how the component processes of the hydrologic system are influenced by climate and vegetation.

3.2.2 Important Linkages Between Climate, Vegetation, and the Hydrologic System

Because the hydrologic system of a drainage basin is characterized by numerous feedback mechanisms that regulate the flow of water in its various states, all hydrologic processes are either directly or indirectly affected by climate. Interception, evaporation, transpiration, infiltration, snowmelt, and runoff are among the most climate-sensitive hydrologic processes.

3.2.2.1 Interception

In the first part of a storm vegetation surfaces are dry and capable of storing moisture as interception storage. Until the vegetation canopy is thoroughly wetted, a

relatively small amount of precipitation reaches the soil surface. Once the interception storage capacity of the vegetation canopy is reached, the amount of precipitation that reaches the soil surface is equal to the difference between the precipitation rate (e.g., intensity) and the rate of evaporation from vegetation surfaces. When precipitation ends, the moisture stored in the vegetation canopy is subsequently lost by evaporation.

The amount of water that is lost to interception storage depends on the species composition and density of the vegetation canopy and on the intensity, timing, and duration of precipitation events. Holding other factors constant, the percentage of annual precipitation lost through this process is highest when annual precipitation consists of short duration, mild intensity storms separated by periods of hot, dry weather. Under these conditions the portion of rainfall intercepted by the vegetation canopy and then evaporated is extremely high.

3.2.2.2 Evaporation

Evaporation is the process whereby water is transformed from a liquid or a solid into a gas by the transfer of heat energy. The rate of evaporation from free water surfaces depends on the vapor pressure differential between the air and the water surface and on wind speed. The vapor pressure of water increases with temperature because of the increase in the kinetic energy of the water molecules. However, because evaporation is proportional to the vapor pressure difference between the air and the water surface, heat must be applied to the water surface as it is cooled or evaporation will cease. In deep lakes and reservoirs, the amount of evaporation also depends on the seasonal variation in temperatures. In Lake Superior, for example, evaporation is highest in the coldest months and lowest during the summer months because water temperature changes much more slowly than does air temperature (Hickman 1940). Thus, evaporation from surface water bodies is not always well correlated with air temperature, seasonally or annually. Evaporation from free water surfaces is indirectly influenced by wind velocity. Increases in wind velocity help to replace saturated air with dry air capable of holding more water vapor. When this air is preheated by flowing over a hot surface, additional energy for evaporation is supplied.

Evaporation from bare soils is governed by the same general climatic factors (temperature and wind) that influence evaporation from free water surfaces. In addition, the molecules of water that escape from the soil as evaporation must overcome the field forces that exist between the soil and water. When the soil column is saturated, the upward movement of water molecules to the surface is high. As the moisture content of the surface soil decreases, so does the loss of moisture by

surface evaporation. Long-term changes in precipitation that influence the concentration of soil moisture can have important effects on the hydrology of a drainage basin by influencing the temperature-regulating effect that evaporation has on the temperature of the land surface and the vegetation canopy.

3.2.2.3 *Transpiration*

Transpiration is the process whereby water is evaporated from within the leaves of plants. It is distinguished from evaporation in that the plant leaves can exhibit significant physiological control over the rate of transpiration through stomatal closure. Transpiration is a complicated process to evaluate, because it is controlled simultaneously by three different factors: the evaporative demand of the atmosphere; the soil-water availability; and the physiological control of the plant through stomatal regulation. Atmospheric driving forces are net radiation; vapor pressure deficit, which combines temperature and humidity; and wind velocity, which controls canopy aerodynamic resistance.

Short-term leaf responses of plants to increasing CO_2 have been well studied. Based on existing evidence, it appears that plants respond differently to higher concentrations of CO_2 , depending on the type of carbon fixation pathway present in a particular plant species (Bjorkman and Pearcy 1983). Plants with a four-carbon pathway (C_4) close their stomata more tightly in the presence of high CO_2 concentrations than do plants with a three-carbon pathway (C_3). Consequently, C_4 plants do not respond as vigorously to the fertilization effects of high CO_2 as do their C_3 counterparts. On the other hand, C_4 plants need less water to maintain their growth because of greater stomatal closure. To date, research has shown that the water-use efficiency (the photosynthesis rate divided by the transpiration rate) of both types of plants increases with ambient CO_2 concentrations. This means that the amount of transpiration per unit of leaf area should decrease for both C_3 and C_4 plants.

In contrast with the well-studied leaf level CO_2 responses, the ecosystem level, long-term responses have had virtually no study, primarily because of the near impossibility of designing a field experimental technique over long time spans. Although scientists are reasonably sure that transpiration rates per unit leaf area will decrease as CO_2 increases, they do not know at the ecosystem level if total leaf area of the plant community may increase, contradicting the leaf-level response. Increasing leaf area would increase canopy interception, decrease soil surface evaporation, decrease incident radiation in lower canopies for photosynthesis, and increase total canopy transpiration among other ecosystem-level feedback responses. In

addition, changes in community species composition and geographical range may occur. As the ambient concentration of CO_2 increases over time, C_4 plants may be able to extend their range to drier conditions, whereas C_3 plants may become dominant over C_4 plants in situations in which the supply of soil moisture is not limiting to plant growth. Given the central role that the vegetation canopy plays in regulating the moisture and sensible heat flux between the atmosphere and the land surface, any such changes in vegetative cover because of direct CO_2 buildup could have an important effect on the hydrology of individual drainage basins.

3.2.2.4 *Infiltration*

Infiltration is the movement of water into the soil through the surface of the ground. The rate at which the soil is capable of absorbing water is called its infiltration capacity. Because the precipitation rate must be greater than the infiltration rate for surface runoff to take place, the infiltration capacities of the soils in a drainage basin play an important role in determining how runoff and streamflow respond to variations in precipitation. The infiltration capacity of a soil is influenced by soil characteristics, by climatic factors, and by vegetation. The seasonal variation in temperature is important because the infiltration capacity of soil is sharply limited by temperatures near and below the freezing point. An increase in the intensity of precipitation events often reduces the infiltration capacity of the soil through soil compaction. An increase in the amount of antecedent precipitation can have a similar effect because precipitation often infiltrates wet soil more slowly than dry soil. One of the most important factors affecting infiltration is the extent of the vegetative cover in a drainage basin. Vegetation protects the soil surface from the impact of intense rainfall. Vegetation also adds humus to the soil and modifies its structure. The clay-humus complex of the soil facilitates the movement of moisture through the soil and enhances infiltration. When vegetation is removed, infiltration rates can fall by 50% or more (Johnson 1940). Hence, long-term changes in precipitation and temperature statistics, which affect either the abundance or mixture of plant species in a drainage basin, may also affect infiltration rates.

3.2.2.5 *Snowmelt*

Initially, snow starts to melt when heat is transferred to the surface of the snowpack from the radiant heat of the sun or by heat conduction from the atmosphere, soil, or rainfall. This meltwater then travels beneath the snow surface and freezes when it comes into contact with colder, underlying snow. As the meltwater freezes, it gives off heat and raises the temperature of the surrounding snowpack. Repeated occurrences of this

freeze-thaw cycle causes the snowpack to “ripen” or to become stratified with layers of ice. Eventually, the density of the snowpack reaches a point at which the maximum water-holding capacity of the snowpack is achieved. When this happens, meltwater in excess of the water-holding capacity of the snowpack moves down through the snowpack. Once this stage of the snowmelt process has been reached, runoff processes take over, and excess meltwater can infiltrate the soil or become overland flow.

As seen from the above discussion, the climatic determinants of snowmelt include antecedent precipitation, which influences the amount of snowpack that can be subjected to snowmelt processes, and variations in air temperature, which influence the meltwater capacity of the snowpack (along with the structure of snow crystals) and the rate of melting caused by the heating of the snow surface. Long-term changes in temperature can also influence the amount of snowpack by changing the elevation of snow lines. Although this phenomenon would decrease snowmelt-derived runoff, the effect on total runoff might be negligible.

3.2.2.6 Runoff

Runoff is comprised of surface and subsurface runoff and base flow. All of these are climate sensitive to varying degrees. Climatic factors that influence surface runoff include the magnitude, type, intensity, and timing of precipitation events, the spatial distribution of precipitation in a drainage basin, and the orientation of storm movement with respect to the channel network. The type of precipitation is important because the runoff response of a drainage basin to rainfall may be fairly immediate, whereas the runoff response to snowfall occurs with time lags. The intensity and duration of rainfall influence the time distribution of runoff. Runoff begins when rainfall exceeds the infiltration capacity of the soil. In some cases, very intense, short-lived storms may produce flooding, whereas a longer, less intense storm may generate more runoff, but no flooding. The timing of precipitation events also affects runoff, because infiltration decreases and runoff increases with the amount of antecedent soil moisture. Thus, mild-intensity storms can, in some cases, produce flooding if the soil is fully saturated by antecedent precipitation. Spatial factors are also important. In many cases, the more unevenly a given amount of rainfall is distributed over a watershed, the greater the amount of runoff that is produced. Runoff is also influenced by the relative movement of storms in a drainage basin. In general, peak flows downstream increase when the direction of storm movement coincides with the direction of streamflow. Finally, surface runoff is indirectly affected by interception, evaporation, and

transpiration, which together reduce the amount of water potentially available for runoff.

Subsurface runoff, sometimes known as interflow, consists of precipitation that infiltrates the soil and then moves laterally through the soil toward rivers and streams. Base flow, as defined earlier, is precipitation that percolates through the soil into groundwater storage and then enters the stream channel with time lags. Over a period of a year or more, the sum of these three components equals the amount of water that appears in streams as streamflow.

3.2.3 Important Parameters of Climate Change

In most instances, it is not possible to characterize the linkages between climate, vegetation, and the hydrologic system of a drainage basin using information about the average annual magnitude of relevant meteorological variables. Although Eagleson (1978) has incorporated precipitation event characteristics into a model that can simulate the change in the parameters (i.e., mean, variance, skewness, and so forth) of streamflow distributions, this approach still requires information about the parameters of the distribution of annual precipitation.

In addition, changes in the mean values of key meteorological variables may not be very useful for characterizing the potential scope of the indirect effects of CO₂ buildup on water resource systems. The remainder of this chapter will show that many water resource systems may be less affected by changes in the mean values of climatic variables than by changes in other parameters of the distributions of these variables and by the rates at which all of these changes occur. Efforts to characterize the potential scope of the indirect effects of CO₂ buildup, at minimum, should take into account the following:

- Effects of changes in climate variability
- Effects of changes in the frequency of occurrence of extreme events
- Effects of changes in the distribution of events over time
- Effects of different rates of climate change

3.2.3.1 Climate Variability

Climate variability is a statistical concept that refers to the magnitude of the fluctuations of meteorological variables about their long-term mean values. To date, almost all of the insights that have been gained from climate models regarding the effects of CO₂ buildup on climate have been about changes in the mean annual values of air temperature, precipitation, evaporation,

and other relevant meteorological variables. In a few cases (Manabe et al. 1981, Wetherald and Manabe 1981), the effects of CO₂ buildup on the seasonal mean values of these variables have been investigated. However, little attention has been paid to the effects that CO₂ buildup could have on climate variability.

The principal effects of CO₂-induced changes in climate variability will probably be related to water supply issues and to society's ability to detect and adjust to climate change. In arid and semiarid regions, the highly variable nature of annual precipitation has often dictated the need to construct large storage reservoirs as a form of insurance against years when annual precipitation is much smaller than its historic mean value. Under these conditions, a change in climate that increased the variance of annual runoff (but did not disturb the mean value of this variable) could potentially increase the maximum storage required to avoid water shortages and thus decrease the reliability of existing storage facilities (Burges and Linsley 1971; Burges and Lettenmaier 1977). Parenthetically, the effects of a reduction in the mean value of annual runoff on the reliability of storage reservoirs could be offset by a reduction in the variance of annual precipitation.

However, reliability is not the only criterion that can be used to evaluate changes in expected system performance caused by CO₂ buildup. Other important criteria include system vulnerability, which refers to the expected magnitude of shortages when they occur, system resiliency, which describes how quickly a system is likely to recover after a shortage has occurred, and system robustness, which describes how well a reservoir system performs over a wide range of supply-demand conditions (Matalas and Fiering 1977; Hashimoto et al. 1982a, 1982b). Placing too much emphasis on the indirect effects of CO₂ buildup on system reliability by water resource planners may obscure more important changes in system performance related to vulnerability and resiliency. This, in turn, presents a challenge to hydrologists and statisticians to develop more comprehensive measures of system performance across alternative climatic states.

Another extremely important aspect of climate variability is the effect it has on society's ability to detect the effects of CO₂ buildup on climate and water resource systems. Other things being equal, the larger the variance of the random component of a variable, such as runoff, the more difficult it is to distinguish a real change in its mean from random fluctuations about a fixed mean. If CO₂ buildup in any way affects the variance of runoff in a drainage basin, then it will be even more difficult to determine whether a real change in the mean or variance of runoff has actually occurred. Because adaptation to climate change depends on the

accuracy of the information about these changes, the possible effects of CO₂ buildup on climate variability need more thorough investigation.

3.2.3.2 *Changes in the Frequency of Extreme Events*

It is important to consider the effects of CO₂ buildup on the frequency of extreme events, such as catastrophic floods and droughts, because of the potential consequences of these events when measured in terms of human suffering and economic loss. Unfortunately, the ability of engineers either to predict these events or to characterize the nature of the risks posed by these events in a probabilistic framework is beset with many problems.

In flood analysis, the problem of prediction has two different dimensions. First, the science of predicting the complex web of meteorological events that gives rise to catastrophic floods is not well developed. Second, the capability to model the hydrologic response of drainage basins to extremely rare combinations of meteorological phenomena has been limited by precipitation measurement problems during severe storms and by the short length of meteorological and hydrologic records. Short record lengths make it difficult to calibrate hydrologic models on peak flows and to evaluate how well a model can simulate the historical pattern of peak discharges for large floods.

Because of the problems associated with trying to predict the peak discharges caused by a given combination of meteorological events, much attention has been focused on using the historical record to characterize the underlying probability distribution from which these events have been drawn. Early work in this field demonstrated, among other things, that (1) many candidate distributions did not fit the historical observations very well (Benson 1968), (2) the parameters of these distributions were often biased in small samples, and (3) these parameters were also extremely sensitive to sample size (Matalas et al. 1975). Although work in this field continues to find better distributions to fit the observed peak discharges of large floods, some hydrologists believe that, in many river basins of the world, the true probabilities associated with the occurrence of catastrophic floods are not known with a high degree of accuracy (Baker 1982; Potter and Walker 1985). Thus, if CO₂ buildup does influence the frequency of floods, it may take society an extremely long time to detect even very large changes.

CO₂ buildup may also influence the frequency of some extreme events, droughts in particular, through its effect on the persistence of streamflow. Since Biblical times, the tendency of dry years to occur together in bunches rather than randomly has drawn

considerable attention among water resource scientists. Whether the phenomenon is real, as Mandelbrot and Wallis (1968, 1969) have claimed, or whether it is symptomatic of nonstationary stream processes (Klemes 1974; Potter 1976), climatically induced changes in the persistence of streamflow could affect the minimum storage required to avoid water shortages in newly constructed reservoirs and the reliability of existing storage facilities (Lettenmaier and Burges 1977, 1978). Unfortunately, statistical estimators of long-term persistence in streamflow records are very sensitive to record length (Wallis 1977). Consequently, the detection of possible changes in these streamflow parameters will be an extremely serious problem. Even if actual changes in these parameters for a particular stream are large, it may take water resource scientists a long time to detect them confidently.

3.2.3.3 *Changes in the Distribution of Events Over Time*

A number of water resource issues are related to the fact that the time distribution of runoff does not coincide with the timing of various water uses. Consequently, changes in CO₂ buildup that indirectly affect the time distribution of runoff can either aggravate or ease the problems that are created when the availability of water does not coincide with the demand for the resource. For example, in many drainage basins the principal rationale for constructing storage facilities is not climate variability but the unevenness of the timing between the supply and the demand for water. In these cases, changes in climate, which lead to a more even distribution of precipitation over the year, may reduce the existing pressure on available supplies. If precipitation became more concentrated seasonally as an indirect result of CO₂ buildup, the change could be either negative or beneficial depending on whether it coincided with periods of peak winter demands.

3.2.3.4 *Importance of the Rate of Climate Change*

The hydrologic system of a drainage basin is driven by short-term changes in weather, not the long-term statistics of climate. Consequently, the response of hydrologic systems to changes in climate, in most cases, will be instantaneous because the same physical laws will apply before and after any such changes. The two major exceptions to this generalization involve the possible effect of changes in climate on (1) the long-run, dynamic equilibrium between natural recharge, discharge, and pumping from groundwater systems, and (2) the composition of the vegetation canopy in a drainage basin.

The importance of time lags between climate change and the response of groundwater systems to this change

may not be very great because the effects of continued groundwater mining on the steady states of these systems probably will be much larger than the effects of possible changes in climate. However, differences in the rate of climate change and the response of vegetation to these changes could be of importance to the hydrologic system of a drainage basin. Within certain limits imposed by temperature, the vegetation canopy in a drainage basin develops to an equilibrium species mix and the density governed by soil moisture, nutrients, and available energy. The vegetation canopy regulates the principal energy and moisture fluxes between the atmosphere and the soil surface, and it plays a central role in modifying soil structure. Given these features, the rate at which the vegetation canopy is able to adjust to changes in temperature and soil moisture will affect many of the component processes in the hydrologic system, particularly in the case of unmanaged forest ecosystems, which may respond very sluggishly to CO₂ buildup (Strain and Cure 1985).

3.3 ANALYSIS OF GENERIC WATER RESOURCE ISSUES

A major premise underlying this research is that CO₂ buildup is not likely to create entirely new water resource issues. Instead, it is assumed that the indirect effects of CO₂ buildup will either consist of changes in the magnitude of current issues or in the geographic distribution of these issues.

Based on this premise, research was undertaken to identify those water resource issues that could in some way be influenced by CO₂-induced changes in climate and vegetation response. The procedures used to select these issues and to identify those that may be most sensitive to the indirect effect of CO₂ buildup have been described in detail by Callaway et al. (1984). These issues are shown in Table 3.1 and are grouped in three generally recognized categories as supply, distribution, and use and reuse issues.

The total set of issues was then screened to determine those most likely to be affected, either adversely or beneficially, by the indirect effects of CO₂ buildup. The resource issues and their potential sensitivity to CO₂ buildup are shown in Table 3.2. The nine water resource issues that were believed to be most highly sensitive to CO₂ buildup were designated to be generic issues. The term generic was adopted on the assumption that although the indirect effects of CO₂ buildup could vary widely according to the physical characteristics and the nature of the social, political, and economic institutions within individual drainage basins, the critical aspects of these issues and the potential

effects of CO₂ buildup on them are independent of these factors.

The remainder of this section examines each of the nine generic issues with reference to (1) their sensitivity to changes in climate and vegetation response, (2) their nonclimatic determinants, and (3) the scope of the potential impacts related to each issue. The data required to more accurately assess the indirect effects of CO₂ buildup on each issue are presented at the end of Section 3.3.

3.3.1 Inadequate Surface Water Supply/Storage

Several projections of global consumptive water use have been made for the year 2000 (Doxiadis 1967; Kalinan and Bykov 1969; Holy 1971; L'Vovich 1979). These estimates are approximately 6×10^3 km³/yr to just under 19×10^3 km³/yr. Despite the wide range of these estimates, all of the authors agree that the expected growth in future water consumption will place increasing strain on global supplies of recoverable freshwater

resources. These estimates all assume that the Earth's climate will remain stable.

3.3.1.1 Sensitivity to Changes in Climate and Vegetation Response

CO₂ buildup has the potential to influence the availability of surface water in two general ways. First, CO₂ buildup may affect mean annual runoff because of changes in (1) patterns of precipitation; (2) air temperature, which affects evaporation and transpiration; and (3) the transpiration rates of plants in the vegetation canopy. Second, CO₂ buildup can influence the balance between surface water supply and demand because of climatically induced changes in water consumption and groundwater availability.

Although it is possible to make some general statements about the effects of changes in precipitation and temperature patterns (from whatever source) on runoff patterns (Eagleson 1978), the variety, variability, and complexity of hydrologic processes make it difficult to do so without fairly specific information about the

Table 3.1
Water Resource Issues That Could be Influenced by CO₂ Buildup

SUPPLY ISSUES	
<u>Surface Water</u>	<u>Groundwater</u>
Flooding	Groundwater Mining
Drought	(Groundwater Overdraft)
Reservoir Sedimentation	
Vegetation Management	
Water Losses From Storage Systems	
Eutrophication	
Effects of Land Use Changes on Basin	
Hydrology	
Inadequate Surface Water Supply/Storage	
DISTRIBUTION ISSUES	
<u>Quantity</u>	<u>Quality</u>
River Sedimentation	Channel Scour/Channel Erosion
Conveyance Losses	
Availability of Potable Water	
USE AND REUSE ISSUES	
<u>Quantity</u>	<u>Quality</u>
Inefficient Irrigation Practices/ Management	Saline Intrusion of Aquifers
Waterlogging (of soils)	Salinity Problems
Groundwater Infiltration Into Municipal Sewer Systems	Waterborne Diseases
Effect of Changing Water Levels	Groundwater Contamination
Navigation Problems	Surface Water Contamination
Conflicts in Use	Acidification of Lakes
Between instream uses	Inadequate Water Treatment Facilities
Between offstream uses	
Between instream and offstream uses	

Source: Callaway et al. 1984.

values of important physical parameters. Nevertheless, under most conditions the relationship between small to moderate changes in mean annual temperature and changes in mean annual runoff is usually negative, whereas the corresponding relationship between precipitation and runoff is positive. Consequently, an increase in mean annual temperature coupled with a decrease in mean annual precipitation should result in less annual runoff, on average, whereas a decrease in temperature combined with increased precipitation should lead to increased runoff. The effects of joint increases or decreases in temperature and precipitation on the direction of the change in mean annual runoff cannot be determined a priori without more specific information about the values of key parameters that influence precipitation and evapotranspiration. Given this information, a general method for calculating these impacts is given in Eagleson (1978).

The magnitude of these changes will depend on the seasonal timing of changes in precipitation and temperature and the nature of the interactions that occur within the hydrologic system because of simultaneous changes in these and other meteorological variables.

Climatically induced changes in the seasonal timing of runoff and in the variability of annual runoff could also have potentially important impacts on the availability of surface water because the relationship between the reliability and size of a reservoir are determined, up to a limit, by these factors. Studies by Lettenmaier and Burges (1977, 1978) and Hoshi et al. (1978) have documented the effects of changes in these parameters on the size of planned reservoirs and the reliability of existing reservoirs.

3.3.1.2 Nonclimatic Determinants

There are two broad, nonclimatic determinants of this issue: (1) the effects that the future rates of population and economic growth will have on the demand for water, and (2) the ability of society to use existing water resources in a more efficient manner. More efficient resource utilization will entail (1) the development and adoption of water-conserving technology, (2) integration of information about the expected effects of CO₂ buildup on climate into water resources planning, and (3) allocation of water supplies based on economic principles.

Table 3.2
Potential Sensitivity of Water Resource Issues to CO₂ Buildup

Issue	Potential Sensitivity to CO ₂ Buildup
Inadequate Surface Water Supply/Storage	HIGH
Groundwater Mining	
Conflicts in Use	
Water Losses From Storage Systems	
Vegetation Management	
Drought	
Flooding	
River Sedimentation	
Salinity Problems	
Waterlogging of Soils	
Saline Intrusion of Aquifers	MODERATE
Surface Water Contamination	
Effects of Land Use Change	
On Basin Hydrology	
Acidification of Lakes	
Waterborne Diseases	
Eutrophication	
Inefficient Irrigation Practices/Management	
Navigation Problems	
Reservoir Sedimentation	LOW
Groundwater Contamination	
Effect of Changing Lake Levels on Aquatic Ecosystems	
Conveyance Losses	
Availability of Potable Water	
Inadequate Water Treatment Facilities	
Channel Scour/Channel Erosion	
Groundwater Infiltration Into Municipal Sewer Systems	

Many technologies now exist to conserve a substantial amount of water used by agriculture, industry, and in the home. According to Postel (1985), the average efficiency of irrigation systems worldwide is only 37%, whereas some new irrigation systems can achieve 98% efficiency. Recycling wastewater represents another potential source of future water savings. For example, in the United States the average number of times a gallon of water is recycled by manufacturing industries is projected to rise from about 3.4 in 1978 to 17.1 by the year 2000 (Culp et al. 1979). Substantial amounts of water can also be saved in home use by adopting more efficient household fixtures. For example, low-flow showerheads use about one-half as much water as convention showerheads, whereas newer, air-assisted models require only about 10% as much water (Brown and Caldwell 1984).

Because it can take up to 50 years to study, plan, authorize, and build a large dam with a service life of another 50 years or more, uncertainty about the indirect effects of CO₂ buildup on the supply and demand for water represents a source of potential problems for water resource planners. Historically, water resource planners have reacted to uncertainty by oversizing reservoirs in efforts to make them "fail-safe." However, this practice can increase the vulnerability of water storage systems to catastrophic failures because few systems of any kind can be made so large or so redundant that failure is impossible (Matalas and Fiering 1977; Hashimoto et al. 1982a, 1982b).

The effect of possible changes in management practices on the future balance between water supply and demand are rarely taken into account in projecting global supplies. Many studies have demonstrated that wasteful uses of water can be minimized by management practices and by the adoption of allocation rules that maximize the net social benefits of water use (Cummings 1972, 1974; Kelso et al. 1973; Crosson et al. 1978). In addition, Vaux (1985) has shown that the use of market-like institutions for transferring water would allow the State of California to adjust to a 50% decrease in surface water availability without having to construct new storage facilities. Although it is true that the increasing scarcity of surface water relative to demand should increase the economic incentives for managing the resource more efficiently, prediction of the gains that may occur in this fashion over the next 50–100 years is also extremely difficult.

3.3.1.3 *Scope of Potential Impacts*

Holding nonclimatic factors constant, the scope of the potential impacts of CO₂ buildup on surface water supplies will depend on the effects of future changes in climate on the magnitude, time distribution, and

variability of runoff. The areas most sensitive to changes in climate will probably lie in arid and semiarid regions; because the amount of runoff that occurs in these areas is smaller and more variable than that in humid regions (Mitchell et al. 1979; Stockton and Boggess 1979).

However, there could also be significant impacts of CO₂-induced climate change on the availability of surface water in densely populated drainage basins in more humid regions. In the Eastern United States, a number of large metropolitan areas now experience, or are expected to have, problems in meeting the growing demand for water. In the United States, the Congressional Budget Office (CBO) has estimated that about 25% of the Nation's large cities will need to develop new supplies by 1990 at a cost of \$2.5–\$3.1 billion annually between 1980 and 1990 (U.S. Congressional Budget Office [U.S. CBO] 1983). Similar problems exist in Europe, where demand already exceeds dependable supply in Bulgaria, Poland, East and West Germany, and Rumania, and on a more local scale in many other nations (United Nations Water Conference [UNWC] 1978). In other regions, notably western Asia, extreme seasonal variability in streamflow necessitates adequate storage facilities both for flood control and dry season supply. However, many developing countries in the region lack such structures because of inadequate economic resources.

Information about the potential effects of hypothetical, not necessarily CO₂-induced, climate changes on mean annual runoff are available for the United States, on a limited basis only, in studies by Stockton and Boggess (1979), Maristany (1979), Nemec and Schaake (1982), and Revelle and Waggoner (1983). None of these studies employed a methodology that would have made it possible to explore the effects of CO₂-induced changes in vegetation response on runoff. With the exception of the study by Nemec and Schaake, all of the remaining studies used empirical models to simulate the effects of changes in mean annual temperature and precipitation on runoff. For example, Stockton and Boggess used an empirical relationship derived by Langbein et al. (1949) to assess the effect of a 2°C increase in mean annual temperature and 10% decrease in mean annual precipitation on estimated mean annual runoff in the 18 large water resource regions in the United States. The estimated change in mean annual runoff associated with this climate modification ranged from –28% in New England to –75% in the Rio Grande region. The average reduction in mean annual runoff for all 18 regions was about 30%. The results from the other studies cited above indicated decreases in runoff that generally fell within this range.

The study by Nemec and Schaake differed from the others in that a systems-based watershed model was

used to evaluate the effects of a variety of hypothetical climate changes on mean annual runoff for the Pease River at Vernon, Texas (a dry basin) and the Leaf River near Collins, Mississippi (a wet basin). They found that a 1°C increase in mean annual temperature and a 10% decrease in mean annual precipitation produced a 50% decrease in mean annual runoff in the dry basin and a 25% reduction in mean annual runoff in the wet basin. This study also investigated the effects of hypothetical changes in climate on the storage required to produce a guaranteed level of reservoir storage or yield. In their analysis, Nemec and Schaake used a yield value equal to 20% of the mean annual runoff for the historical streamflow data and a reliability level of about 84% (e.g., an average 16% of the time, supply is less than demand). Their results showed that a combined 1°C increase in mean annual temperature and a 10% reduction in mean annual precipitation caused a 220% increase in required storage on the Pease River and a 120% increase in required storage in the Leaf River. However, neither of these rivers is regulated for water supply, and the yield target for the two rivers was selected arbitrarily. More important, neither this study nor any of the others cited previously have attempted to assess the effects of possible CO₂-induced changes in climate variability on either runoff or reservoir storage requirements. As a result, conclusions from this and other studies about the effects of hypothetical changes in climate on the water supply of these two basins are extremely limited.

The possible effects of CO₂ induced changes in vegetation resource on runoff were investigated by Aston (1984), who used a systems-based watershed model to simulate the effects of a doubling of stomatal resistance on runoff in two catchments in Australia. The results of this analysis indicated a 40 to 90% increase in runoff because of this effect. In a related study, Idso and Brazel (1984) examined the combined effects of simulated changes in climate and vegetation response on runoff in 12 drainage basins in Arizona. Their results indicated that a 2°C rise in temperature and a 10% drop in precipitation corresponded with simulated changes in mean annual runoff ranging -30 to -60%. Inclusion of the effect of a doubling of CO₂ concentrations on stomatal resistance, along with the changes in climate described above resulted in simulated changes in mean annual runoff ranging from 5 to 60%.

The last two studies suffered from three primary sources of inaccuracy. First, best estimates from global climate models predict a variety of region specific climatic shifts. Near surface air temperatures are predicted to increase anywhere from 1° to 8°C, depending on locale. Along with increasing potential evaporation, higher air temperatures would lengthen

the "growing season" or effective transpiration season of many plant communities. Precipitation may change from -25% to +25%, with possible shifts in seasonal periodicity. There may be changes in cloudiness that would affect photosynthesis and increase in vapor pressure deficit that increases both atmospheric evaporative demand and canopy resistance by inducing partial stomatal closure. These changes have obvious consequences for surface evaporation and transpiration that cannot be resolved until the climate scenario can be reasonably well predicted.

Second, there are no published studies, including those cited above, that treat the ecosystem level responses, particularly of leaf area, that may very well occur under conditions of increasing global CO₂. With additional photosynthate available to plants because of higher water-use efficiency, additional leaf-area growth would be a quite predictable response as each plant attempts to compete for more light. The community level response may be a new equilibrium between leaf area and environment (Grier and Running 1977) that would still consume most of the available soil water. Canopy interception and reevaporation could subsequently increase, reducing the water that percolates through the soil. Plants may be able to grow deeper root systems and extract more soil water than before. Given the potential for increased canopy leaf area, interception, growing season length, and other factors, conclusions suggesting major increases in runoff are probably premature.

Finally, neither study took into account the influence of elevation on plant water use. As elevation increases the density of the vegetation canopy decreases and the importance of transpiration also declines. This means that, at higher elevations, the effect of CO₂-induced temperature changes on evaporation will probably be stronger than the fertilizing effect of CO₂ on transpiration, in which case Idso and Brazel would appear to have overstated the effects of increasing stomatal resistance on runoff.

Clearly, beyond the leaf-level research that has already been done, new advances in vegetation responses to CO₂ must incorporate more holistic ecosystem models with watershed hydrology models, preferably with state-of-the-art global climate simulations.

3.3.2 Groundwater Mining

If water that is stored in glaciers in the form of ice is excluded from consideration, groundwater represents the largest source of freshwater available in the Earth's hydrosphere. Groundwater mining of this resource occurs when, over a period of years, the mean annual

rate of water lost from groundwater storage by pumping and natural discharge exceeds the mean annual rate at which these sources can be recharged by natural processes. This practice may result in (1) increased pumping costs to groundwater users, (2) actual or effective loss of the source of supply, (3) reduced base flow in streams and rivers, (4) saltwater intrusion of coastal aquifers, (5) property damages caused by land subsidence, and (6) declines in groundwater quality at greater pumping depths.

3.3.2.1 *Sensitivity to Changes in Climate and Vegetation Response*

When water is pumped from an aquifer, the natural equilibrium between the prevailing recharge and discharge is disrupted. The water that is withdrawn from an aquifer may be derived from a decrease in storage, an increase in recharge, a decrease in the discharge of the aquifer into lakes and streams, or a decrease in the amount of evapotranspiration from the saturated zone. As pumping continues, the aquifer is drawn down and groundwater that was being lost from the system either through evapotranspiration from the saturated zone or through discharge into streams, lakes, or the ocean can now be captured for storage. If pumping stabilizes, recharge and discharge may again reach equilibrium. In that context, groundwater mining may be sensitive to the effects of CO₂ buildup on climate and vegetation response through changes in recharge or in the components of capture (discharge and evapotranspiration losses) and, indirectly, through changes in pumping.

Four basic sources contribute to the natural inflow of water to groundwater storage systems: (1) replenishment by percolation of precipitation from the soil surface; (2) seepage from river and stream channels; (3) deep percolation of return flows from irrigation enterprises; and (4) lateral inflow from adjacent groundwater basins.

The effects of CO₂-induced climate changes on groundwater recharge will depend, first, on the structure of the groundwater formations in a drainage basin (which determines the principal source of recharge) and, second, on the sensitivity of the relevant recharge mechanisms to changes in various temperature and precipitation parameters. The interaction between these two factors can be illustrated by examining the relationship between the intensity of precipitation and recharge. In a drainage basin in which the principal source of recharge is through streamflow, the rate of recharge will be determined by the difference between the rate of rainfall (intensity) and the infiltration rate. As long as the potential rate of infiltration is greater than the rainfall intensity, no surface runoff will occur. When the intensity of a storm becomes great enough such that the rate of rainfall exceeds the infiltration rate,

surface runoff occurs and becomes a potential source of supply for an aquifer that is recharged by streamflow. However, for an aquifer that is recharged primarily by percolation, a storm that produces no surface runoff can still provide recharge because rainfall that infiltrates the soil is potentially available for percolation.

Aquifer recharge rates will also depend on changes in temperature and transpiration losses. If other factors remain the same, an increase in temperature will have the effect of reducing the proportion of additional precipitation that is potentially available for recharge through the various mechanisms described above. However, changes in temperature, along with possible changes in the water-use efficiency of plants in the vegetation canopy will probably have a more profound influence on the ability of aquifers to capture evapotranspiration losses from the saturated zone. In that regard, increases in temperature would have the effect of increasing plant transpiration and reducing the amount of water available for capture in the saturated zone. If CO₂ buildup decreases the water use of plants in the vegetation canopy and if the resulting decrease in soil water demands are not offset by changes in the species mix of vegetation, then more water would be available in the saturated zone for capture. Changes in the species mix of vegetation could also affect the infiltration capacity of the soil and potentially could indirectly influence groundwater recharge mechanisms.

Finally, CO₂-induced changes in temperature patterns can potentially influence groundwater mining through the effects that these changes have on the rate of withdrawal from an aquifer. At least three effects must be taken into consideration: (1) the direct influence of changes in temperature on the demand for groundwater, (2) the indirect effects of changes in temperature on groundwater development caused by changes in the availability of surface water, and (3) the impact of the withdrawal of surface water from a source that is conjunctively linked to a groundwater source. Where water is used conjunctively (Maknoon and Burges 1978), the rate of withdrawal from river, lake, and reservoir sources may influence natural recharge and discharge rates from the groundwater source.

3.3.2.2 *Nonclimatic Determinants*

The principal nonclimatic determinants of groundwater mining are related to (1) the underlying demographic and economic forces that will determine the rate of development and depletion of groundwater supplies, (2) future changes in groundwater management practices and the legal status of groundwater resources, and (3) factors that affect the development and adoption of water-conserving technologies on the part of water users.

Given the limited nature of the surface water resource, groundwater development on a global scale is increasing and is doing so at an increasing rate (United Nations [U.N.] 1960, 1976b, 1979). Much of this development is taking place in arid and semiarid regions where recharge to consolidated groundwater formations is limited by low precipitation and where surface water development has greatly reduced the recharge of alluvial formations through streamflow. Prediction of the rates of future groundwater pumping in these and other nations at any degree of confidence is complicated by the complex dynamics of long-term population growth and economic development. However, it seems reasonable to suggest that groundwater mining may become a more, rather than less, serious problem globally over the next 100 years and that the effects of economic and demographic development on this issue in many regions probably will be greater than the indirect effects of CO₂ buildup.

The alternatives currently available for reducing the magnitude of this issue can be extreme, involving large-scale, interbasin water transfers (U.S. Army Corps of Engineers [U.S. COE] 1982) or substantial changes in the law regarding groundwater. For example, in Arizona, where groundwater overdrafts have recently been averaging 3.0×10^6 m³/yr (Briggs 1983), a groundwater management code was enacted in 1980 that will have a severe impact on irrigated agriculture in that state. On the other hand, a great deal of international research is now being focused on artificial recharge (U.N. 1975) as a method for increasing the availability of water supplies in arid regions. Storing water in this manner augments total supplies by reducing evapotranspiration losses in reservoirs and from streambanks, while it reduces the size of surface water storage systems required to meet a given level of reliability.

3.3.2.3 *Scope of Potential Impacts*

CO₂-induced changes in climate may magnify or reduce the problems associated with groundwater mining. However, the extent of these impacts is extremely difficult to characterize, even in general terms, because of the complex nature of the relationship between climatic factors and different recharge mechanisms and the problems associated with predicting the effects of nonclimatic determinants on the magnitude of this issue.

The most serious groundwater mining problems to arise over the next 100 years will occur in arid or semiarid regions. In general, recharge rates in these areas are low because of high evapotranspiration losses in conjunction with low precipitation. Alluvial groundwater systems in these areas are particularly vulnerable to surface water development that can drastically reduce the amount

of recharge that occurs because of streamflow through desert valleys. In these areas, changes in climate and vegetation probably will not have a profound direct effect on the equilibrium of groundwater systems. In many cases the important effects of CO₂-induced changes in climate on groundwater mining in these regions, either beneficial or detrimental, will probably be indirect because of changes in surface water availability and the demand for both surface and groundwater.

3.3.3 *Conflicts in Use*

Conflicts among different types of water uses include (1) instream uses, such as hydroelectric power generation and maintenance of instream flows for fish runs, recreation, and preservation of water quality; (2) offstream uses, such as irrigation versus energy resource development; and (3) instream and offstream uses, such as irrigation versus hydroelectric power generation.

Distinguishing between competition for water and conflicts in use may be useful. Economically, competition for water arises whenever the resource is scarce (i.e., its opportunity cost is positive). In a free market, competition allocates these scarce resources in a manner that maximizes the value of these resources to society. Conflicts in use occur when water is scarce; however, resource scarcity by itself is not a sufficient condition for conflict. Regarding water, conflicts in use usually arise because users of surface and groundwater are physically interdependent. Consequently, the action of a single user can adversely affect the actions of other users, through detrimental changes in water quantity and water quality. This problem is exacerbated by institutional factors: existing legal mechanisms for defining access to, and the ownership of, freshwater do not generally provide the correct incentives for reducing the problems created by mutually interfering use (Coase 1960; Ditweiler 1975; Kneese and Schultze 1975).

A simple example involving the conflict between the upstream use of water for waste assimilation and the downstream use of water for drinking and sanitation illustrates these points. As long as the supply of water is plentiful enough to effectively dilute wastes without adversely affecting drinking water quality, no problem exists. However, when the supply of water is small in relation to the demand for waste assimilation, the free market for water generally will not produce a socially optimal allocation of the resource between the two conflicting uses. The reason for this is that, in an unregulated market, the individuals or firms using the stream to assimilate wastes do not have incentives to consider the effects of their actions on downstream users. Therefore, more waste is discharged into the

stream than is socially optimal for all users. Under these conditions, conflict between the two groups of users occurs.

The type of conflict described in the example could be resolved by requiring upstream users to compensate downstream users for the decline in water quality. This type of solution does not eliminate competition between users. It provides a basis for reducing or eliminating conflicts, and it also creates an allocation of water between the two users, which provides greater benefits to society as a whole (Baumol and Oates 1975).

3.3.3.1 *Sensitivity to Changes in Climate and Vegetation Response*

The sensitivity of this issue to changes in climate and vegetation response depends largely on the type of conflict involved. Conflicts in water use generally will be sensitive to changes in climate and vegetation response, which affect both runoff and the demand for water. Therefore, it should be stressed once again that changes in climate affecting the variability of annual and seasonal runoff and the timing of runoff in relation to the demand for water may have a substantially greater impact on the magnitude of individual conflicts than will changes in mean annual runoff.

Two examples illustrate the importance of changes in the variability and timing of runoff in determining the future magnitude of individual conflicts. First, an increase in the variability of annual runoff may affect instream conflicts related to water quality and water quantity tradeoffs by requiring the construction of more expensive water treatment and larger water storage facilities to compensate for more frequent periods of low flows. Second, an increase in temperature that coincides with peak demands for hydroelectric power and irrigation water in the summer months would have a much greater impact on the conflict between these uses than an increase in temperature that was concentrated in off-peak periods.

3.3.3.2 *Nonclimatic Determinants*

The nonclimatic determinants related to this issue are, first, future changes in population and economic activity that will affect the development and use of surface and groundwater resources within individual drainage basins and, second, improvements in the efficiency of water use by technological means or through the adoption of better management practices, or both.

The importance of the first two factors has already been addressed in connection with other generic issues covered in this chapter and requires no further elaboration. Better management, however, raises questions about the distributive nature of conflicts in use.

Earlier, it was noted that these conflicts can often be traced to institutional and legal sources. In theory, many conflicts over water use could be reduced by redefining the property rights accorded to water users. However, attempts to redefine the property rights of water users will usually have distributive consequences; consequently, there tends to be much resistance to changes in water laws.

Therefore, one can expect that, although CO₂ buildup may increase the impetus for changing water laws in many nations in order to deal with heightened conflicts over water, this will also increase the political resistance to these legal changes on the part of users who may be adversely affected.

3.3.3.3 *Scope of Potential Impacts*

Wherever freshwater is economically scarce, there is conflict over its use. The impacts of these conflicts, which can be measured economically or physically by the distributive tradeoffs, can be substantial, particularly in developed nations. In the United States, for example, estimates of the foregone value of water to all recreational users, because of the lack of pollution control, have been placed at between \$6 and \$17 × 10⁹/yr (1978 U.S. dollars) (Heintz et al. 1976; Freeman 1979; Mills and Feenberg 1979). Conflicts over water use can become particularly intense in dry regions where water is scarce. For example, in a study focusing on the development of steam electric generating plants in the Four Corners area in the Southwestern United States, Gisser et al. (1979) showed that the reduction in agricultural water use necessary to allow this development would generate a regional income loss of about \$5 × 10⁸/yr. In the lower Colorado River Basin, where return flows from upstream irrigation water users increase the salinity of surface water used by downstream irrigators, it has been estimated that each 1 ppm increase in dissolved solids causes \$230,000 damages per year (Evans 1975). Technological and institutional solutions have been demonstrated for salinity and resource misallocation problems in the Colorado River Basin and elsewhere. However, disagreement over who will share the costs and benefits of these solutions has made it difficult to resolve such conflicts.

Only very limited conclusions can be drawn about the scope of the potential impacts of CO₂ buildup on this issue. Because of the foreseeably large impacts of nonclimatic determinants, the level of conflict over the next 100 years is virtually impossible to predict. One can only suggest that, as conflicts become more intense as a result of expected population and economic growth, the incentives to allocate and use water more efficiently will also increase. In addition, the impacts of CO₂ buildup on

this issue will depend on the nature of conflicts and the changes in climate and vegetation response that occur within specific drainage basins and, as such, are difficult to generalize. Finally, it is difficult to characterize the potential scope of the indirect effects of CO₂ buildup on this issue because the magnitude of these impacts will also depend, to some extent, on the ability of water users to adapt to CO₂-induced changes in climate and vegetation response once they have been detected.

3.3.4 Water Losses From Storage Systems

The primary cause of water losses from natural and manmade storage systems is through evaporation. Additional losses may occur as a result of seepage through permeable soils or reservoir banks or through excess leakage through the face of a dam because of faulty construction practices. In virtually all cases, the design of manmade storage systems takes into account evaporation and seepage losses. As long as these design estimates are reasonably accurate, these losses do not pose a serious problem to the computed reliability of storage reservoirs under the existing climatic regime for which those calculations were made. Cases in which actual losses exceed design losses can result in increased salinity concentrations in the system, a rise in the water table (which may be beneficial for groundwater users, but possibly detrimental to adjacent land uses dependent on the depth of the water table), property damage caused by the reservoir leakage, and, most important, a lowering of the reliability of the storage system.

3.3.4.1 Sensitivity to Changes in Climate and Vegetation Response

The principal climatic factors that affect evaporation from free water surfaces were discussed earlier in this chapter. Of these, changes in air temperature can be expected to exert the greatest influence on the evaporation of water from storage systems. If changes in the seasonal distribution of temperature occur, they have the potential to influence the timing of evaporation losses, but there will be time lags in deeper bodies of water. Although changes in the timing of evaporation losses will not be as important as changes in the magnitude of annual evaporation losses in reservoirs with multiyear storage, these changes may affect the reliability of systems in which storage is seasonal. CO₂-induced changes in vegetation density in the area surrounding a reservoir may exert a small effect on reservoir evaporation because of changes in the amount of energy advected from these surfaces. (The effects of CO₂ buildup on transpiration-related water losses is covered in Section 3.3.5.)

3.3.4.2 Nonclimatic Determinants

The magnitude of the effects of CO₂-induced changes in temperature on evaporative losses from surface water storage systems will also depend on the number and size of the reservoirs exposed to these changes and the rate at which methods for reducing evaporation are developed and adopted. Methods that can be used to reduce evaporation from surface water storage systems include minimizing the ratio of surface area to storage, the use of floating covers (Cooley 1970), granular materials (Meyers and Fraser 1970), and monomolecular films (Mansfield 1955). However, with the exception of the first approach, none of these methods has proven sufficiently cost-effective to use on large lakes or reservoirs. This situation may change if CO₂ buildup adversely affects water supplies over large areas. In that case, the increasing economic and social value of water may make these measures economically feasible.

3.3.4.3 Scope of Potential Impacts

The principal effects of CO₂-induced climate changes on evaporation from surface water storage systems will consist of changes in the mean annual storage of reservoirs. The impacts of these changes, either beneficial or detrimental, will probably be most pronounced in the arid regions currently subject to the highest losses. In the United States, this includes the western parts of Texas and Oklahoma; all of New Mexico and Arizona; and the southern portions of Utah, Nevada, and California (National Oceanic and Atmospheric Administration [NOAA] 1982). Water losses from surface storage in this region can be substantial. For example, at Lake Mead, Nevada, annual average evaporation has been estimated to range between 167 and 224 cm/yr, depending on the method used to calculate evaporation (Morton 1979). This translates into a mean annual evaporation loss of roughly 1.2×10^9 m³/yr. This is enough water to irrigate about 85,000 ha of cropland in the region.

3.3.5 Vegetation Management

Vegetation management refers to the use of chemicals, mechanical methods, or silviculture practices to reduce transpiration losses from aquatic weeds, phreatophytes, and other forms of naturally occurring vegetation. The primary objective of vegetation management is increased water yields. In the case of prolific aquatic weeds, such as water hyacinth and hydrilla, additional benefits are derived from physically removing these weeds from water courses where they tend to diminish the free flow of water, restrict navigation, clog conveyance systems and water intake pipes, and reduce water quality. In

some areas of the world, removal of aquatic vegetation also helps to control the habitat for waterborne disease vectors.

3.3.5.1 *Sensitivity to Changes in Climate and Vegetation Response*

The need to increase water yields in a drainage basin by means of vegetation management will depend on (1) the effects of CO₂-induced changes in temperature and precipitation on transpiration and runoff, (2) the effects of CO₂-induced changes in plant water-use efficiency on transpiration, and (3) the interactive effects between CO₂-induced climate change and vegetation response on the abundance and species mix of vegetation within individual drainage basins.

Holding the latter two effects constant, it seems likely that any CO₂-induced increases in temperature, if they coincide seasonally with periods of active vegetation growth, would probably increase transpiration and reduce runoff. This should enhance the benefits to be derived from vegetation management, whereas a decrease in seasonally relevant temperatures would presumably lessen the need for this type of streamflow augmentation.

The statements given above presume no ecosystem changes. However, CO₂ buildup also has the potential to alter the abundance and species mix of vegetation within the natural ecosystem of many drainage basins worldwide. These ecosystem changes may have a significant effect on transpiration losses within individual drainage basins. Unfortunately, the data on these effects are too limited to characterize the magnitude or direction of these effects on transpiration losses at the drainage basin level.

3.3.5.2 *Nonclimatic Determinants*

In the United States, at least, the decision to increase water yields or clear weeds through vegetation management is usually based on the outcome of benefit-cost analysis. In that framework, the benefits to be derived from augmenting streamflow are weighed against the costs incurred in terms of other resources that are foregone. These foregone resource benefits are typically related to increased flood hazards, increased erosion and sedimentation, loss of merchantable timber resources, and the destruction of wildlife habitats and aesthetic resources (Bowes et al. 1984). The principal effects of CO₂ buildup will be to change the economic benefits associated with the augmented levels of streamflow. For example, if CO₂ buildup directly or indirectly increases transpiration losses and reduces mean annual runoff, then the value of the additional runoff made possible by vegetation management will presumably rise.

It is also possible that the value of some resources that might be foregone as a result of future vegetation management practices would also be affected by CO₂ buildup. For example, if CO₂ buildup indirectly affected the frequency of flooding in a drainage basin, this would also influence the value of forest ecosystems in retarding runoff and reducing flood damages.

However, the economic value of these foregone resources and additional supplies of water will also depend on a host of other factors unrelated to CO₂ buildup, which will affect the supply and demand for the relevant market and nonmarket resources involved.

3.3.5.3 *Scope of Potential Impacts*

The scope of CO₂ buildup on the relevant physical dimensions of this issue, transpiration and runoff, are particularly difficult to predict because of the primary importance of future changes in the abundance and species mix of vegetation within individual drainage basins. However, based on the potential importance of the ratio of evapotranspiration to runoff to this issue, it seems reasonable to suggest that the areas of greatest sensitivity will be those in which this ratio is relatively high, namely in arid and semiarid regions. In these areas, a small CO₂-induced change in this ratio will have a relatively larger effect on the potential need to augment streamflow by means of vegetation management than in more humid regions.

Some idea of the existing physical potential for augmenting streamflow through vegetation management can be gained from fairly recent studies of the Colorado River Basin in the Southwestern United States. Estimates of the amount of runoff that can be augmented in this basin by vegetation management varies greatly, depending on vegetation type (Clary et al. 1974; Horton and Campbell 1974). For the basin, as a whole, Hibbert (1979) has estimated that a maximum of 7.4×10^9 m³ of streamflow could be recovered annually from the basin. This represents about 40% of the annual flow of the Colorado River at Lee Ferry, Arizona. In a related study, Ffolliott and Thorud (1974) estimated that the potential water savings that could be realized from vegetation management in Arizona watersheds was about 1.25×10^9 m³/yr. However, as Hibbert (1979) has pointed out, these estimates of potential water savings are currently in excess of the economically feasible yields that can be realized given current values for the resources that would be displaced by these practices.

3.3.6 *Drought*

Conflicting definitions of drought make it difficult to identify and characterize drought events and their

impacts. Meteorologists are concerned with drought as a period of below normal precipitation; agronomists view drought in the context of insufficient soil moisture to support crops; hydrologists view droughts as periods of below normal streamflow and depleted reservoir storage; and economists are concerned with drought as it affects societies' productive and consumptive activities (Dracup et al. 1980). In this report, the term drought is used to refer to extended periods of unusually low streamflow that are long enough to threaten the adequacy of existing water supplies.

3.3.6.1 *Sensitivity to Changes in Climate and Vegetation Response*

Droughts, as defined above, are caused by extended periods of below-normal precipitation. This produces a sharp decrease in runoff, streamflow, and groundwater recharge because of streamflow. The effects of droughts on vegetation and soil moisture are also severe. During droughts, the volume of moisture withdrawn from storage by transpiration increases, and soil moisture levels fall. As soil moisture becomes depleted, several things happen: vegetation begins to wilt, the density of the vegetation canopy decreases, the soil becomes more exposed to direct sunlight, and more water is required to maintain plant growth under these conditions. Eventually, the plants in the vegetation canopy will die, and if drought conditions are prolonged, changes in soil structure and chemistry will begin to take place with the onset of desertification.

The response of the hydrologic system to drought conditions in a deterministic framework is reasonably straightforward. However, much less is known about the characteristics of drought in a probabilistic framework. The problems associated with the characterization of droughts are illustrated by the ongoing debate about the apparent tendency of periods of low flows to be grouped together. The apparent cyclical character of droughts was demonstrated for rivers in the United States in two early studies by Hoyt and Langbein (1944) and Langbein (1958) who observed a tendency of periods of low flows to bunch together. Because peak flows did not follow the same pattern, the explanation for this phenomenon did not appear to be low-order serial correlation. At about the same time, Hurst (1951, 1957) pointed out the same characteristic bunching pattern in the low flows of the Nile River and, based on these observations, suggested the existence of climatically induced low frequency signals (long-term persistence) in streamflow records. A number of different theories have been advanced to explain the Hurst effect. These have been reviewed by Wallis and O'Connell (1973) and Klemes (1974). Two different explanations of this phenomenon stand out above the others. The first,

introduced by Mandelbrot and Van Ness (1968) and Mandelbrot and Wallis (1968, 1969), attributes the Hurst phenomenon to infinite memory in hydrologic processes, as characterized in hydrologic records by very long spans of interdependence. An alternative theory, first advanced by Klemes (1974), attributes the Hurst effect to nonstationary hydrologic processes, as evidenced by shifts in the means of historical streamflow records.

Evidence to support the existence of infinite memory processes in precipitation records can be found in the work of Stockton and Boggess (1979) and Mitchell et al. (1979). However, other investigations of precipitation records on a global scale (Dehsara and Cehak 1970) and in North America (Yevjevich 1964, 1972; Potter 1979) suggest that a large majority of precipitation records can be characterized by short memory processes and, thus, show no evidence of long-term persistence. According to Potter (1979), the Hurst effect in many precipitation records may be explained by changes in the instruments and methods used to collect and measure precipitation, movements in precipitation gauging stations, and changes in the natural and physical environment around precipitation gauges. The phenomenon of long-term persistence in streamflow records has also been called into question by Wallis and Matalas (1970) and Wallis (1977), who demonstrated that small sample estimators of the Hurst coefficient were biased and extremely sensitive to change in sample size (record length). In related research, Matalas and Fiering (1977) questioned the use of geochronological methods (including tree-ring analysis) to overcome the problems associated with short geophysical records. They showed that the estimates of climatic variability obtained by these are biased.

The debate over the apparent persistence of droughts illustrates how difficult it is to characterize the underlying probability distributions of extreme events by using short geophysical records. This problem also makes it difficult to characterize the sensitivity of streamflow distributions to possible CO₂-induced changes in climate and vegetation response. These difficulties are further compounded by the fact that the current generation of climate models was not designed to assess the effects of CO₂ buildup on climate in a probabilistic framework. Thus, the possibility that CO₂ buildup may influence the frequency and duration of droughts cannot be discounted, but the capability to characterize, let alone predict, these impacts with any degree of confidence is not yet well developed.

3.3.6.2 *Nonclimatic Determinants*

Although there is some evidence that removal of vegetation by humans can adversely influence the precipitation regimes in very dry climates (Charney

1975), the physical dimensions of prolonged periods of below average streamflow are determined by natural forces. Drought impacts on the other hand, are related to the strain that these natural events place on the balance (or imbalance) between the services provided to society by the hydrologic system of a drainage basin and the demands placed on that system by water users. As such, the magnitude of drought impacts will depend critically on (1) the sensitivity of water uses in a drainage basin to decreases in the availability of water for a period of a few years, (2) the flexibility of water planning and management institutions to respond to drought conditions, and (3) the amount of long-term carryover storage available in the drainage basin.

3.3.6.3 *Scope of Potential Impacts*

Reliable global estimates are not available, but several individual drought examples help give an indication of the potential magnitude of future impacts. The 1972–1973 Afro-Asian drought coincided with a 4% drop in world grain production and is identified as the principal cause of this reduction (Burton and Kates 1978). During the six-year drought in the Sahel region of Africa in the early 1970s, it has been estimated that 100,000 lives were lost because of the resulting malnutrition and disease (Loftin 1978), and large areas of land were lost because of desertification, a process in which drought is a major catalyst. Finally, in the California drought of 1976–1977 an estimated \$2.4 billion was lost in gross income to the State's farm production and agriculture-related industries (U.S. General Accounting Office [U.S. GAO] 1977). These examples illustrate the potential magnitude of drought impacts that may affect dryland and irrigated farming, livestock rearing, hydroelectricity generation, fisheries, industrial and municipal water users, and others.

According to Kovda (1980) 50–60% of the continental surfaces of the Earth have a drought frequency of 10–15%; i.e., drought is experienced 10–15 years out of every century. As mentioned earlier, areas that are most subject to recurrent droughts are those in which, relatively, the variations in annual rainfall are highest. These areas include the far-western and southwestern portions of the United States, the west coast and eastern tip of South America, all of northern Africa above 15° N latitude, a large portion of central Asia, and large portions of western and central Australia. The total affected area, excluding drought-prone areas above the Arctic Circle, amounts to about one-fifth of the Earth's solid surface (Petterssen 1958). In addition, the economic damages from drought tend to be greater in developed nations, whereas impacts on human health are generally more severe in developing countries (Burton and Kates 1978).

3.3.7 Flooding

A flood is any high flow of water that overtops the natural or artificial banks of a stream or river and encroaches on the adjacent lands (Dalrymple 1964). The elevation of a peak flow of this magnitude is referred to commonly as the flood stage. Flood events can be measured by the frequency (or recurrence interval) associated with a peak flow of a given magnitude, the duration of the peak flows above the flood stage at a particular location, the associated peak discharge of the flood, and the area inundated by the flood. The causes of flooding include (1) intense rainfall; (2) rapid or early snowmelt, either alone or in conjunction with intense rainfall; (3) ice jams on streams and rivers; (4) rain-induced mudflows that block the stream channel; and (5) unplanned releases of water from storage reservoirs caused by abnormally high runoff.

3.3.7.1 *Sensitivity to Changes in Climate and Vegetation Response*

With the possible exception of flooding caused by ice jams beneath bridges, all floods are produced by runoff that exceeds the capacity of the stream channel. As such, the physical magnitude of a flood depends on all of the climatic factors influencing runoff. These factors include type of precipitation, intensity, duration, and frequency of storms and the timing between storms.

Surface runoff generally occurs after interception and soil storage demands have been satisfied. When this point is reached, the drainage basin will produce a runoff pulse, the rate of which (holding rainfall intensity and duration constant) depends largely on factors affecting evapotranspiration and infiltration (Eagleson 1978). As such, the risk of flooding in a basin from a single storm varies directly with the intensity and duration of storms. The amount of runoff produced from multiple storm events will depend on the intensity and duration of individual storms and on the interarrival times, or spacing, between individual storm events. If storms are spaced far apart, the moisture stored in the vegetative canopy and the soil will be subject to evapotranspiration for a longer period of time than will occur if interarrival times are short. Thus, more space will be available to store the moisture from subsequent storms before runoff can occur.

CO₂-induced changes in the intensity, duration, frequency, and timing of storms have the potential to influence flooding. However, floods are by definition extreme events, as are the meteorological events that provide the water for them. This aspect of flooding, combined with the fact that individual flood events are relatively isolated geographically, raises serious questions about the ability of the scientific community

to predict and characterize the effects CO₂ buildup has on flood risks in river basins around the world. To make such predictions would require extremely detailed information about the effects of CO₂ buildup on the expected changes in the intensity, duration, and timing of precipitation events, far out on the tails of the distributions of these variables and on a very detailed geographic level. The capability to provide accurate information about the effects of CO₂ buildup on these variables in a probabilistic framework at the necessary level of geographic detail is not yet well developed. Even if this capability were to exist, the scientific community would still have to confront the problems related to predicting and characterizing the probabilities of flood events under current climate conditions. (These problems were addressed earlier in Section 3.2.3 and were also discussed in connection with droughts.)

The extent of vegetative cover in a drainage basin also influences flooding. CO₂ buildup could affect not only the transpiration of soil moisture by natural vegetation, but, more important, it could affect the interception storage capacity of vegetative cover in a drainage basin and the ability of vegetation to spread the flow of water over the surface of the land and mechanically retard runoff. However, both the first- and second-order effects of CO₂ buildup on transpiration and on the extent and structure of vegetative cover in natural ecosystems are very difficult to predict.

3.3.7.2 Nonclimatic Determinants

There is no evidence of general change in the occurrence of large (i.e., low frequency) floods on the great rivers of the world (United Nations Environment Programme [UNEP] 1982). However, the volume of discharge from high and medium frequency floods has been increasing because of urbanization upstream and the widespread removal of trees and vegetation in rural areas (McPherson 1974). Flood hazards and flood losses are growing in many nations of the world, although at varying rates, because of the encroachment of human settlement and economic activity on floodplains (UNEP 1981). Thus, the magnitude of flooding impacts is increasing, even when climate is viewed as essentially stable.

Impacts of flooding can be controlled by structural means and regulation of the types of activity and structures that are permitted on the floodplain. In the United States most of the economically feasible major flood control projects have either been constructed or are almost completed (U.S. Water Resources Council [U.S. WRC] 1978). Consequently, the majority of efforts in the United States to regulate flooding consist of statutory forms of floodplain regulations (James 1975). However, if CO₂-induced climate changes greatly

increase the magnitude and frequency of floods in the United States, economic feasibility of currently marginal structural flood control measures could be improved.

3.3.7.3 Scope of Potential Impacts

The impacts of flooding primarily involve loss of life and damage to property. Sufficient information to characterize the magnitude of these impacts caused by CO₂-induced climate change does not currently exist. However, some insight may be gained by a brief discussion of the magnitude of current impacts.

In general, property damage caused by flooding is greater in developed nations (primarily in urban areas), whereas substantial loss of life is most often associated with flooding in developing nations, particularly in Asia and the Pacific. Between 1947 and 1970, over 173,000 deaths were attributed directly to flooding worldwide, averaging 7500 deaths per year (U.N. 1976a).

Global estimates of average annual economic damages caused by flooding are extremely crude. However, one estimate that has received some attention places this figure at about $\$16 \times 10^9/\text{yr}$ (U.N. 1976a). Average annual damages by country vary widely. For Japan this figure has been estimated to be about $\$600 \times 10^6/\text{yr}$, whereas in India, a substantially larger nation, average annual damages caused by flooding are about $\$200 \times 10^6/\text{yr}$ (U.N. 1976a). By comparison, estimates of average annual flooding damages in the United States range from $\$1.8 \times 10^9$ to $\$3.8 \times 10^9$ (Burton and Kates 1978; U.S. WRC 1978; U.S. Congress, Office of Technology Assessment [U.S. OTA] 1980).

3.3.8 River Sedimentation

Under natural conditions, soil is constantly being eroded from land surfaces by the action of water, wind, ice, and gravity. It is then transported as sediment to rivers where it is carried downstream until it is eventually deposited in lakes, estuaries, and oceans. Under steady-state conditions, most rivers achieve a state of equilibrium with respect to the supply of sediment and the transport capacity of the channel. However, when this equilibrium is disrupted, either by man or by climate, problems can arise, including aggradation or degradation of the stream channel, changes in water quality, and impairment of the aesthetic value of water for recreational use.

3.3.8.1 Sensitivity to Changes in Climate and Vegetation Response

River sedimentation is sensitive to changes in climate and vegetation through the effects that variations in precipitation, temperature, and the extent of vegetative

cover have directly on sheet erosion and the transport of sediment to streams and indirectly on channel erosion due to runoff-induced changes in streamflow. Results of a number of studies (Ellison 1945; Wischmeier and Smith 1958; Williams 1969) indicate that soil loss due to sheet erosion is most heavily influenced by the intensity rather than the magnitude of rainfall. The timing of precipitation events can also affect sheet erosion and the transport of sediments to streams, in some cases producing extreme results. For example, the highly sinuous, relatively narrow, and deep Cimarron River channel in southwestern Kansas was completely destroyed by a combination of high peak discharges and unusually large loads of sediment during the flood of 1914 (Schumm and Lichty 1963). Studies by Anderson (1970) and Gupta and Fox (1974) have documented similar occurrences in other parts of the United States.

The effect of possible temperature changes on river sedimentation will probably not be as important as the effects of changes in the intensity and timing of rainfall. However, because temperature influences soil evaporation, changes in temperature can also affect runoff. This may influence the amount of material detached from the soil by surface runoff, as well as the amount of material transported to streams by runoff. Thus, more precipitation is generally required to produce a given amount of sediment in a warm climate than a cool one (L'Vovich 1979). Finally, the abundance and type of vegetation in a drainage basin influences sediment yield by dissipating some of the energy in raindrops before they reach the soil, by retarding runoff water, by influencing the susceptibility of soils to erosion, and by reducing soil moisture through evapotranspiration (Flaxman 1972; Blackburn 1975; Elwell and Stocking 1975).

Studies of several drainage basins in the United States by Langbein and Schumm (1958) and Schumm (1971) indicate that mean annual sediment yields are strongly dependent on precipitation regimes and the vegetation associated with these regimes. Under arid conditions (mean annual precipitation less than 300 mm), sediment yields vary directly with precipitation. In drainage basins in which mean annual precipitation lies between 300 and 1150 mm, this relationship is reversed, and increased precipitation is associated with reductions in sediment yield because of enhanced vegetation. In basins in which mean annual precipitation is greater than 1150 mm, annual sediment yields do not appear to be significantly influenced by increases in precipitation.

3.3.8.2 *Nonclimatic Determinants*

With the possible exception of changes in sediment yields caused by possible CO₂-induced changes in the frequency of catastrophic floods, the impacts of human activities

on river sedimentation probably will be much more profound than those of climate. The most important nonclimatic determinants of river sedimentation-related problems consist of land-use practices that disturb the natural vegetative covering in a drainage basin and the physical alteration of the streambed and channel because of flow regulation structures. Examples of land-use practices that affect sheet erosion are soil tillage and overgrazing of range and pastureland (Wade and Heady 1978), deforestation (Painter et al. 1974), and the conversion of the natural landscape to a variety of urban uses. In the latter case, an early study by Holeman and Geiger (1959) documented a threefold increase in the annual sediment yield from the Lake Bancroft watershed in Virginia over a 10-year period of rapid urbanization from 1942 to 1952. The construction of dams in streams and rivers also affects river sedimentation because of upstream channel aggradation, which reduces the capacity of a channel to carry sediment, and downstream channel degradation, which often increases erosion in tributary watersheds. The sediment yield of streams, in turn, can be reduced by adopting tillage and silvicultural practices that reduce sheet erosion and by the construction of sediment basins and check dams to control gully erosion.

Two factors about the effects of these nonclimatic determinants on river sedimentation need to be stressed. First, the effects of land-use changes on river sedimentation can be very dramatic and could overshadow the influences of CO₂ buildup. More needs to be learned about the effects of human activity on erosion and sedimentation before it will be possible to gauge the possible effects of CO₂-induced changes in climate and vegetation response on this issue. Second, the relevant impacts of man on river sedimentation are extremely difficult to predict over long periods of time.

3.3.8.3 *Scope of Potential Impacts*

The principal problems created by increases in river sedimentation include (1) reduction in channel depths required to maintain navigation; (2) increases in flood damages caused by channel aggradation and sediment deposits; (3) clogging of irrigation works; (4) increases in turbidity, which reduces light transmission through water and inhibits the growth of underwater plants that are a primary food source for aquatic life; (5) increases in the concentration of nutrients, herbicides and pesticides, trace metals, and radioactive compounds that adhere to eroded materials; (6) interference with spawning grounds and other habitats of aquatic wildlife; and (7) degradation of the aesthetic quality of water.

No a priori basis exists for determining the relationship between CO₂ buildup and the magnitude of these problems at this time. However, current estimates of

the damages caused by sedimentation over a large area may give a rough indication of the magnitude of future problems. For the United States, it has been estimated that the total annual damages caused by sedimentation (exclusive of reservoir sedimentation) are between $\$375 \times 10^6$ and $\$500 \times 10^6$ (American Society of Civil Engineers [ASCE] 1969; Wade and Heady 1976). Comparable estimates for other countries could not be found in the literature. However, one may surmise that the magnitude of sediment-related problems are probably most severe in Asia, Australia, and North America, which have the highest sediment yields in relation to land area (Holeman 1968; L'Vovich 1979).

3.3.9 Salinity Problems

The salinity-related problems discussed in this section are due primarily to the use of saline water for irrigating crops and to overirrigation, which causes saline water in the water table to rise into the root zone. The range of salt contents in irrigation waters ranges from about 100 total dissolved solids (TDS) mg/l to 4000 TDS mg/l. The original sources of these salts are natural: the primary minerals found in the soils and the exposed rocks of the Earth's crust. The soluble constituents of these minerals are gradually released over time because of decomposition and erosion. In humid climates, heavy rains usually leach these salts into the groundwater from which they are transported to streams and oceans in relatively low concentrations. In arid regions, on the other hand, there is less precipitation available to naturally leach and transport these salts from the soil. In addition, the high evaporation rates characteristic of arid climates tend to produce higher concentrations of salts in groundwater and soils.

Locally high concentrations of soil salts can seriously retard the yields of many different crops (Maas and Hoffman 1977). Irrigators in these regions have responded typically to this problem by using water (over and above that required to maintain crop growth) to leach these salts below the root zone where their danger to local crops is minimized. This practice of leaching increases the salinity concentration in the water that is returned to streams and groundwater sources for subsequent use. The reuse of this water by other irrigators can cause additional increases in surface and groundwater salinity in the lower parts of a basin. In the long run, excessive leaching can actually lead to increases in soil salinity because the concentration of soil salts must always be equal to or greater than the concentration of salts in the irrigation water used for leaching.

3.3.9.1 *Sensitivity to Changes in Climate and Vegetation Response*

As indicated in Section 3.3.9, the impacts of human activity on soil and surface water salinity can be profound. However, changes in climate potentially can influence the concentration of salts in soils and surface waters in several different ways. Over very long periods of time, changes in mean annual precipitation and temperature can affect the processes of mineral weathering and natural leaching of soluble salts that dictate steady-state concentrations of soil salts. Long-term changes in climate variability could also have an impact on these processes because flooding in arid regions is known to be an important agent in weathering and in bringing salts to the soil surface from great depths (Chebotarev 1955; Choudari and Sharma 1984). Hypotheses about the more immediate impacts of CO_2 -induced changes in mean annual precipitation and temperature on soil salinity can be derived from a simple model of the salt balance in the soil (Bresler 1967). In general, there is a negative relationship between changes in mean annual precipitation and mean annual salt concentration in the soil and a positive relationship between changes in mean temperature and the mean annual concentration of soil salts. The salt balance in surface waters can be expected to respond to any possible changes in climate in a similar fashion.

3.3.9.2 *Nonclimatic Determinants*

Low soil permeability, high temperatures, and low rainfall contribute to the tendency of salt to accumulate in soils, but the most important contributing factor to salinity problems is poor irrigation management. The impact of the leaching practices described earlier in this section are best illustrated by the case of the Colorado River where, according to Evans (1975), 37% of all salts originate from irrigation as opposed to 47% due to natural sources. (The remaining 16% is caused by evaporation, water exports, and municipal/industrial wastes.)

Potential solutions to salinity problems have been addressed by Skogerboe and Walker (1981). They include (1) the lining of canals to reduce salt pickup; (2) changes in cultural practices, such as switching to more salt-tolerant plants and the adoption of special soil-tillage practices; (3) the application of surface-active agents that reduce evapotranspiration and conserve soil moisture; and (4) improved irrigation scheduling methods. However, the relatively low value of irrigated crops in some regions and the lack of economic incentives for irrigators to improve the quality of water for

downstream use has slowed the adoption of these practices in the United States and elsewhere. This suggests strongly that institutional, rather than technical, changes may be required to adequately address salinity problems in the future.

3.3.9.3 *Scope of Potential Impacts*

Probable indirect effects of CO₂ buildup on surface water and soil salinity problems will consist of changes in water quality and changes in agricultural productivity on irrigated cropland. Consequently, the largest impacts of CO₂-induced climate change probably will be concentrated in arid and semiarid regions where extensive irrigation development has taken place or is expected to occur. According to Yaron (1981), about one-third of all irrigated land in the world is currently affected by salinity problems, but in some areas of Israel, India, Northern Africa, and the Southwestern United States, 50–75% of the land may be affected. According to El-Gabaly (1977), salinity problems are currently serious, or are expected to become serious, in virtually all of the countries of the Middle and Near East.

3.4 CASE STUDY FINDINGS—SALT RIVER BASIN

A case study site was selected to explore the feasibility of different methods for characterizing the effects of CO₂ buildup on relevant, generic water resource issues. The site chosen for this research was the Salt River Basin in central Arizona. The Salt River Basin was selected for study primarily because (1) extensive annual and interseasonal climate variability is present at the site, (2) the generic issues are well represented in the basin, (3) upstream discharge records in the basin reflect relatively little intervention by man, and (4) high-quality data are readily available from relevant public and private agencies.

The Salt River Basin includes the drainages of the Salt and Verde Rivers including Tonto Creek. These drainages encompass approximately 34,000 km² and constitute the major source of streamflow and groundwater recharge for Phoenix and adjacent municipalities in the desert lowlands. The combined mean annual runoff from these drainages is about 1500×10^6 m³, based on the instrumental record for the period 1931–1982. Figure 3.2 is a drawing of the reservoir system in the Salt River Basin. The total reservoir storage capacity in the six reservoirs is about 2430×10^6 m³, about 80% of which is concentrated in the reservoirs on the Salt River. These structures are owned and operated by the Salt River Project (SRP). The SRP service area supplied by these storage reservoirs is about 96,000 ha, of which about

one-half is currently irrigated. Total water deliveries within the SRP service area averaged about 1600×10^6 m³/yr during the 1970s. About 75% of this amount was used annually for agriculture and about 30% was supplied for various municipal and industrial uses. For practical reasons, the focus of this study is limited to the SRP service area.

3.4.1 Research Design of the Case Studies

The primary objective of the case study phase of the research was to characterize the effects of hypothetical changes in climate on the availability of freshwater and on other selected water resource issues in a portion of the Salt River Basin. The types of models that were used in the case study and the relevant information linkages between the models needed to address the case study objectives are shown in Figure 3.3.

3.4.1.1 *System Models*

The system described in Figure 3.3 consists of three types of models: (1) multiple regression rainfall-runoff models for the Salt and Verde Rivers, respectively; (2) a stochastic streamflow generation model; and (3) a reservoir simulation model for the Salt River Basin reservoir system.

Two multiple regression models were used in this study to simulate the effects of change in monthly precipitation and temperatures in the basin on the monthly discharges of the Salt and Verde Rivers. The two regression models were virtually identical in structure. The dependent variable in each model was the natural log of the adjusted monthly discharge into the upstream reservoir on each river, Roosevelt Lake on the Salt and Horseshoe Lake on the Verde. The gauged discharge records for both rivers were adjusted to take into account upstream diversions and ungauged discharges from springs and other sources. The independent variables in each model included multistation averages for monthly temperature and precipitation in the two drainage basins. Dummy variables were used in both models to adjust the intercept terms and the temperature and precipitation variables to reflect seasonal differences in the response of runoff to climatic variation in each basin. Distributed lags (Dhrymes 1971) were also employed in the two models to capture the delayed effects of soil moisture carryover, base flow, and snowmelt on runoff.

The parameters of the two models were estimated by using monthly time series observations for temperature, precipitation, and adjusted discharges for the period 1931–1982. Earlier portions of the instrumental records for both rivers were not used based on evidence that

these earlier data were not homogenous with the 1931–1982 records. The parameters were estimated using a variant of generalized least squares (Cochrane and Orcut 1949) to adjust for the adverse effects of serially correlated residuals on the efficiency of the parameter estimates. The Salt and Verde River regression models explained about 80% of the variation in the monthly discharge of the two rivers. The application of standard time series forecasting tests (Theil 1971) revealed that, on average, both models showed very little bias in their predictions. However, both models forecast significantly higher than actual monthly flows in very dry, hot years. This, most probably, is because there were too few historical observations about the effects of 1°–2°C above normal increases in temperature to accurately characterize the true structure of the relationship between climate and runoff in this temperature range. This problem was critical during the December through April runoff period for which the models predicted small anomalous increases in runoff because of increases in temperature. This phenomenon may be consistent with the effects of small increases in air temperature on snowmelt, whereas increases in air temperature on the order of 1°–2°C would almost surely reduce runoff because of below average snowfall and above average evaporation. There is some evidence that the

performance of these models under very dry conditions in winter and early spring can be improved by using daily climate and streamflow data and by adding a moisture storage component to both models (Tangborn and Rasmussen 1976).

A stochastic streamflow model was used in the analysis to generate synthetic streamflow sequences that would reflect the effects of climatically induced changes in mean monthly streamflows. The model used to do this consisted of a two-site generator for the annual flows of the Salt and Verde Rivers in concert with a disaggregation submodel to break the annual flows down to a monthly basis. The annual model was an autoregressive moving average model (ARMA) developed by Lettenmaier and Burges (1977). The seasonal submodel used to disaggregate the annual flows followed the approach of Lane (1979). The parameters of the ARMA model were estimated by the quantile method (Hoshi et al. 1984) with the same adjusted monthly discharge records that were used to estimate the parameters of the regression models. Estimates of the first-order autocorrelation coefficients for both rivers were not significantly different from zero. Therefore, the annual generation model selected was a zero-order autoregressive model (AR [0]) that is consistent with normally distributed white noise, uncorrelated in time.

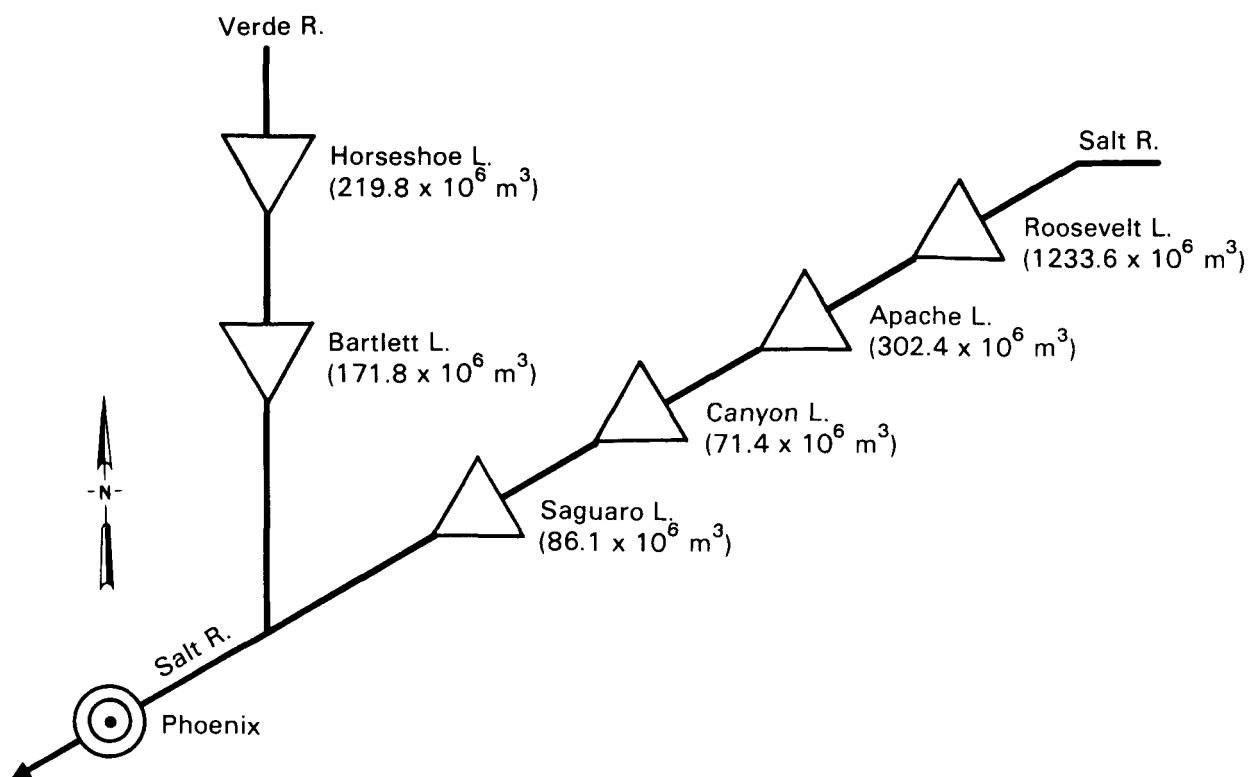


Figure 3.2. Salt River Basin reservoir system (storage capacities are in parentheses).

A reservoir simulation model was used in the analysis to characterize the effects of climatically induced changes in mean monthly streamflows on the ability of the reservoir system to meet projected water requirements. This model was developed by the U.S. Bureau of Reclamation for the Salt River Basin. Basically, the model keeps track of the monthly water balance in the reservoir system and uses available water in storage, supplemented by groundwater pumping, to meet monthly water requirements in the Salt River Project service area.

3.4.1.2 System Simulation

The system of models shown in Figure 3.3 initially was designed to simulate the effects of climatically induced changes in streamflow within the basin in the following manner. The numbers by the models in Figure 3.3 are referenced in the text below to assist the reader in following the steps used to simulate the effects of different temperature and precipitation regimes on reservoir performance.

Step (1) involved modification of the temperature and precipitation inputs to the Salt and Verde Rivers' regression models to reflect simulated changes in climate. For this study, changes in climate were simulated by altering the monthly values in the instrumental temperature and precipitation records, consistent with hypothetical changes in mean monthly temperatures

and precipitation over the entire record. (The base-case (current) climate was simulated by using the actual historic record; otherwise, there were no differences in the procedures used to simulate the base-case results from those used in Cases 1 through 7.) After the climate records had been revised, the multivariate regression models were used in step (2) to simulate the effects of these changes on monthly streamflows at the reservoir inflow gauges described earlier. The climatically altered streamflow records for the two rivers, in both sets of models, were then used to compute the revised parameter estimates (e.g., mean, variance) for the monthly flow distributions of the two rivers.

In step (3), these revised parameter estimates were used to adjust the mean monthly streamflow parameters in the streamflow generation model to reflect the effects of climate change. The streamflow model was then used to generate 100 monthly synthetic streamflow sequences of 50-years' duration for each river. In the final step (4), the synthetic streamflow sequences generated by the streamflow model were passed through the monthly reservoir simulation model to assess the effects of hypothetical climate changes (including changes in the frequency of droughts) on the ability of the storage system to meet projected water requirements. The model results were also used to help characterize the effects of climate-induced changes in streamflow on flooding, supplemental groundwater pumping, surface

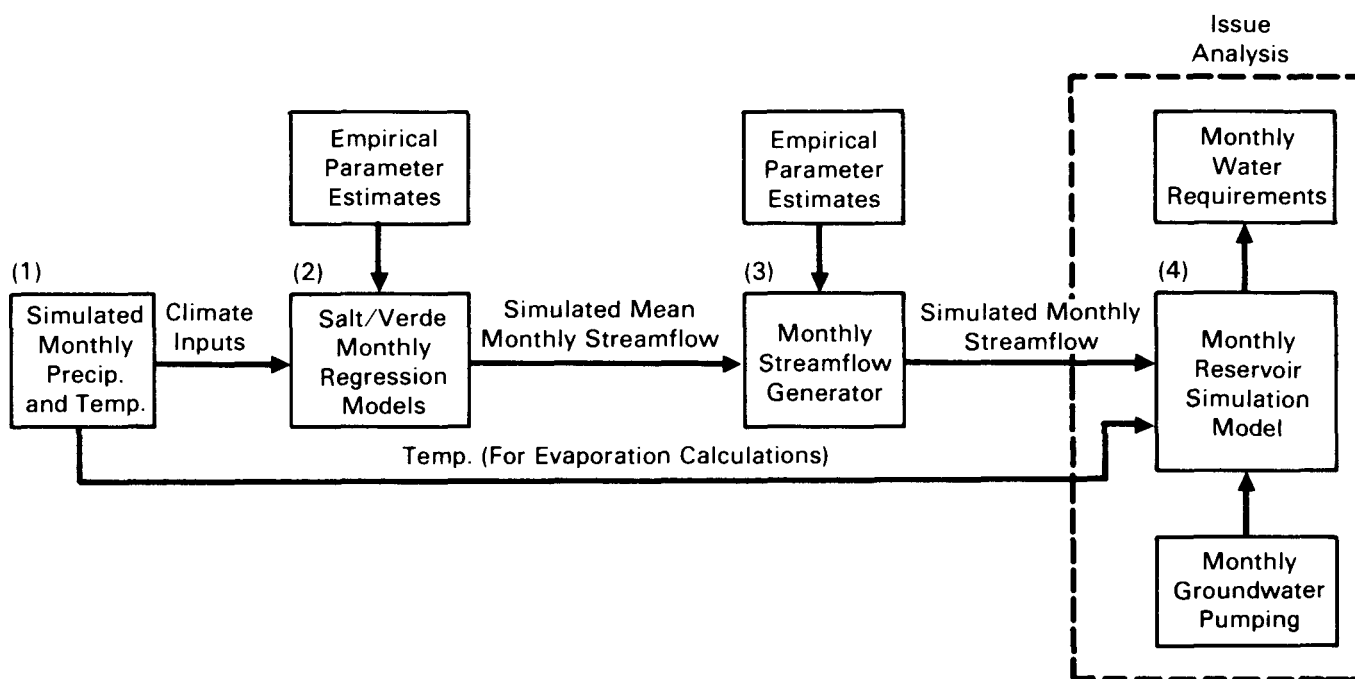


Figure 3.3. Schematic diagram of Salt River Basin modeling system.

water losses due to increased evaporation, and on the need to increase runoff in the basin by intensive vegetation management.

3.4.2 Case Study Findings

3.4.2.1 Characterization of Effects on Surface Water Availability

The modeling system described in Section 3.4.1 was used to simulate the effects of eight different modified temperature and precipitation regimes on the performance of the Salt River Basin reservoir system. The baseline climate and streamflow conditions used in the analysis are shown in Table 3.3 for the Salt River and Table 3.4 for the Verde River. The temperature and precipitation modifications are outlined in Table 3.5. The climate modifications used in this analysis should be regarded as hypothetical. Information from climate models generally suggests that mean annual temperature for this region of the United States will increase by about 0.5°–2.5°C as a result of a doubling of the atmospheric CO₂ concentrations. No such consensus exists about the direction or the magnitude of the regional change in mean annual precipitation caused by a doubling of the CO₂ concentration. Because of the lack of agreement about the effects of CO₂ increases on the local climate, modifications based on climate model results would have been difficult to establish. Therefore, a different approach was taken. Given the robustness of the Salt River Basin Reservoir system to historical variations in climate, the climate modifications were designed to test how vulnerable the system might be to adverse changes in climate if they occurred. These adverse climate changes consisted of increases

Table 3.3
Baseline Climate and Streamflow Conditions
for the Salt River Basin

Month	Weighted Mean		Mean Discharge
	Temp. (°C)	Precip. (cm)	10 ⁶ m ³
Oct.	19.9	2.9	34.8
Nov.	12.7	2.9	27.8
Dec.	8.4	4.7	59.9
Jan.	7.6	4.4	81.4
Feb.	9.8	3.9	128.7
Mar.	12.6	4.2	197.3
Apr.	17.2	1.6	159.2
May	22.1	0.9	80.5
June	27.3	0.8	39.3
July	30.1	3.8	38.8
Aug.	28.7	5.2	58.6
Sept.	25.9	3.6	47.0

Note: Based on instrumental record from 1931 to 1982.

Table 3.4
Baseline Climate and Streamflow Conditions
for the Verde River Basin

Month	Weighted Mean		Mean Discharge
	Temp. (°C)	Precip. (cm)	10 ⁶ m ³
Oct.	11.9	3.5	21.0
Nov.	5.9	3.6	23.9
Dec.	2.3	5.1	43.3
Jan.	1.1	4.9	46.1
Feb.	2.9	5.3	75.1
Mar.	5.2	4.9	128.3
Apr.	9.4	2.7	68.0
May	13.7	1.4	22.6
June	18.8	1.1	16.9
July	22.0	6.4	20.7
Aug.	21.9	8.2	31.0
Sept.	17.3	4.2	25.2

Note: Based on instrumental record from 1931 to 1982.

in temperature (which were generally consistent with current information about the effects of CO₂ buildup) coupled with small decreases in precipitation, which were about 5–20% below normal. Cases 0 through 4 represent the parametric portions of the analysis. Case 0 in this table is the base case, and does not involve climate modifications. In Cases 1 through 4, monthly temperature and precipitation values in the historical record were adjusted so that the indicated changes in mean annual temperature and precipitation would be distributed across the months of the year according to their current distributions. This was done to allow comparison between the results in this study and others that examine annual, as opposed to monthly, changes in these variables.

Cases 5 and 6 were developed on the basis of inspecting the monthly climate records on a year-by-year basis in the two drainages to determine the possible relationship between monthly temperature and precipitation during years of well-below normal streamflow. During these infrequent periods, it was found that 1°–2°C increases in temperature were frequently accompanied by decreases in monthly precipitation of 15–30% or more during the December through April runoff period. This phenomenon largely is due to the fact that the conditions that bring extremely warm temperatures to the basin during winter and early spring produce very little snowfall, which usually constitutes the bulk of precipitation during these months. Approximations of these conditions were examined in Cases 5 and 6. In case 6, monthly temperature and precipitation values were maintained at base-case levels. However, the Hurst coefficient of the streamflow generation model was adjusted upward to reflect a sharp increase in the frequency of droughts in the basin.

Some of the major results of the simulations that were conducted using the eight cases are shown in Table 3.6 and Table 3.7. These two tables differ with respect to the water requirements imposed on the reservoir system. Water requirements in Table 3.6 reflect the currently projected estimate of the Salt River Project for $1013 \times 10^6 \text{ m}^3$ in the year 2035 (Salt River Project 1981). Table 3.7 reflects actual water deliveries by the Salt River Project in 1980, amounting to about $1480 \times 10^6 \text{ m}^3$.

The results of the simulations must be viewed in light of the anomalous runoff response indicated by the Salt and Verde Rivers regression models to changes in temperature during the runoff period. In comparison to the base case, a 2°C increase in mean annual temperature and 10% decrease in mean annual precipitation (Case 4) resulted in a 17% decrease in the combined mean annual flow of the two rivers. This is a significantly smaller reduction in streamflow than the greater than 40% decrease reported by Stockton and Boggess (1979) for the lower Colorado River Basin. This discrepancy is partly caused by the relatively poor performance of the Salt and Verde Rivers regression models under hot, dry conditions. Given this shortcoming, the results shown for Cases 5 and 6 may give a better indication of potential future problems in the basin than do Cases 1 through 4. The reduction in mean annual reservoir inflow for these two cases is about 32 and 35% respectively, much closer to the values reported by Stockton and Boggess (1979). None of the results in Tables 3.6 and 3.7, nor the results reported by Stockton and Boggess, should be treated as predictions about the effect of CO_2 -induced climate change on the availability of surface water in the Salt River Basin.

The major conclusion to be drawn from Table 3.6 is that, if the future water requirement projections of the Salt River Project are reasonably accurate,

climatically induced decreases in streamflow on the order of magnitude described for all cases in this study should not create serious problems in meeting projected demands. This is due, first, to the multiyear storage capacity of the reservoirs in the Salt River Basin, approximately $2.4 \times 10^9 \text{ m}^3$ and, second, to the large usable groundwater pumping capacity in the basin, which was limited to $67.8 \times 10^6 \text{ m}^3/\text{mo}$ in the analysis to simulate voluntary compliance with the new state groundwater code. Average monthly reservoir storage never fell below about 72% capacity, whereas average annual groundwater pumping never exceeded about 43% of the usable capacity in the system (Table 3.6).

An increase in the demand for water coinciding with 1980 water deliveries had a slightly adverse effect on reservoir performance (Table 3.7). In Case 2 and Cases 4 through 7, the reliability of the system fell below 100% because of the increased pressure that these higher demands placed on the storage capacity of the reservoir system and the groundwater pumping capacity of the Salt River Project. In the worst case (Case 6) the system failed to meet the target demand level, on average, in 17.8 of the 600 months (50 years) for which reservoir operation was simulated. This translates into a system reliability level of 97.03%, which is extremely high. However, in those years when shortages did occur, the average annual supply shortfall associated with this level of reliability was $268.1 \times 10^6 \text{ m}^3$, or about 18% of the target demand level. Thus, although the reservoir did not fail very often in the worst case, the magnitude of the shortfalls that did occur were relatively large. This demonstrates that a system that is extremely reliable also may be extremely vulnerable to very large (but infrequent) shortages.

Comparison of the results presented in Tables 3.6 and 3.7 illustrates, to some extent, the importance of considering the effects that changes in water-demand

Table 3.5
Definition of Climate Modifications

Case No.	Change in Mean Annual Temperature ($^\circ\text{C}$)	Precipitation Modification
0	No change	No change
1	+1.0	-5% in mean annual precipitation
2	+1.0	-10% in mean annual precipitation
3	+2.0	-5% in mean annual precipitation
4	+2.0	-10% in mean annual precipitation
5	+1.0	-10% in dry ^a months; 20% in wet ^b months
6	+2.0	-10% in dry months; 20% in wet months
7	No change	No change; more frequent droughts

^aDry months are defined as the period from May through November.

^bWet months are defined as the period from December through April.

Table 3.6
Simulated Effects of Hypothetical Changes in Mean Monthly Temperatures
and Precipitation on Reservoir Performance for the Salt River Basin
(Arizona) Using Projected 2035 Water Requirements ($1013 \times 10^6 \text{ m}^3$)

Simulation Case No.	Avg. Annual Reservoir Inflow (10^6 m^3)	Avg. Monthly Reservoir Storage (10^6 m^3)	Avg. Annual Groundwater Pumping (10^6 m^3)	Avg. Annual Supply Shortfall ^a (10^6 m^3)	System Reliability (%)	Avg. Annual Reservoir Evaporation (10^6 m^3)
0	1475.4	2136.9	167.2	0.00	100.0	176.4
1	1343.8	2052.9	216.3	0.00	100.0	180.5
2	1209.8	1987.3	252.6	0.00	100.0	175.6
3	1368.3	2034.1	225.8	0.00	100.0	189.9
4	1228.9	1967.6	265.7	0.00	100.0	184.7
5	1002.1	1840.3	332.3	0.00	100.0	165.2
6	978.6	1783.2	353.5	0.00	100.0	171.6
7	1475.4	2134.2	171.9	0.00	100.0	176.2

^aAverage is computed only for years in which shortfalls occur.

patterns may have on the future supply-demand balance in a basin.

In the Salt River Basin, Salt River Project (SRP) officials are predicting a significant decrease over time in the amount of water that will be consumed (Salt River Project 1981). Specifically, the projected water-use estimate for the year 2035 assumes that high prices for agricultural land and water in combination with a new state groundwater code, which makes it difficult to expand irrigated acreage, will lead to a sharp reduction in the amount of water used to irrigate crops in the Salt River Valley. The 2035 water-use scenario also assumes that higher water prices will increase incentives to reduce per capita water use through conservation measures and the adoption of water conserving technological changes. These same types of incentives are expected to increase the economic feasibility of projects to reduce conveyance losses and regulate water deliveries in a more efficient, but more expensive, manner. Based on the results of

Table 3.6, these changes will make the reservoir system in the basin fail-safe, even if runoff is reduced by 30–40%.

3.4.2.2 Characterization of Effects on Other Generic Issues

The results in Tables 3.6 and 3.7, in addition to shedding some light on the issue of inadequate surface water supplies, also provide some limited insights about the potential effects of climatically induced changes in streamflow on the following generic water resource issues: flooding, drought, groundwater mining, surface water losses and, to a very limited extent, vegetation management.

Flooding. Flooding in and around the city of Phoenix is infrequent because in all but very wet years, all of the runoff from the basin is captured behind SRP reservoirs, and the channel of the Salt River through Phoenix is virtually dry. This management policy reflects the

Table 3.7
Simulated Effects of Hypothetical Changes in Mean Monthly Temperatures
and Precipitation on Reservoir Performance for the Salt River Basin
(Arizona) Using Actual 1980 Water Demands ($1480 \times 10^6 \text{ m}^3$)

Simulation Case No.	Avg. Annual Reservoir Inflow (10^6 m^3)	Avg. Monthly Reservoir Storage (10^6 m^3)	Avg. Annual Groundwater Pumping (10^6 m^3)	Avg. Annual Supply Shortfall ^a (10^6 m^3)	System Reliability (%)	Avg. Annual Reservoir Evaporation (10^6 m^3)
0	1475.4	1753.6	410.5	0.00	100.00	153.5
1	1343.8	1594.9	483.2	0.00	100.00	150.4
2	1209.8	1413.1	543.9	0.99	99.98	141.1
3	1368.3	1581.9	487.2	0.00	100.00	161.9
4	1228.9	1400.9	545.2	2.10	99.96	148.6
5	1002.1	972.6	625.9	131.90	98.28	104.6
6	978.6	883.2	635.0	268.10	97.03	102.1
7	1475.4	1607.6	454.9	0.86	99.96	143.8

^aAverage is computed only for years in which shortfalls occur.

very high value of the water stored in the reservoirs and, consequently, the high cost of releasing water in anticipation of an extremely rare event. Flooding in the Salt River Valley occurred most recently in the winter of 1965 (Aldridge 1970) and again on several occasions during the period from March 1978 to June 1980 (Wise 1978; Mann and Rohne 1983). All of these floods were caused by unplanned releases of water from already full SRP reservoirs because of higher-than-expected runoff from upstream drainages. These events followed a 25-year period of below-average runoff during which project reservoirs were kept as full as possible to ensure adequate surface water supplies. More recently, potential flooding problems were averted in the winter and spring months of 1982–1983 because of a series of managed reservoir spills before the runoff season. The adoption of this new policy reflected a changed attitude on the part of SRP officials about the tradeoffs between the objectives of flood control and water supply in a risk environment. Whether this change in attitude was because of the development of better streamflow forecasting techniques or to new information added to the historical record about flooding in recent years is unclear.

As suggested above, flooding in the Salt River Basin has both natural and human components. As expected, simulated drier and hotter conditions reduced the natural causes of flooding because of decreases in the magnitude of peak flows entering SRP reservoirs. The simulated reduction in water consumption for the year 2035 (Table 3.6) reduced the management-related causes of flooding by making additional storage available in the reservoir to regulate flooding. In the high-water demand scenarios (Table 3.7) the amount of storage that could be switched from water supply to flood control purposes was reduced, intensifying flood-management problems. The interplay between man and nature at this level makes a situation in the basin possible where a reduction in the natural risk of flooding could be offset by the need to manage the reservoir system exclusively for water supply. Under these conditions, more flooding might be allowed to occur simply because the consequences of guessing that there would be a flood, subsequently releasing water, and then being wrong would be worse than the consequences of flooding.

Drought. In estimating the parameters of the annual streamflow generation model, no evidence of a low-frequency signal could be found in the 1931–1982 discharge records of the Salt or Verde Rivers. This conflicts with the findings of Smith and Stockton (1981), who found evidence for a 22-year drought cycle in a much longer reconstructed record for these two rivers. The effects of adding this type of low-frequency signal to the discharge records of the Salt and Verde Rivers

was illustrated previously by Case 7 in Tables 3.6 and 3.7. The effects of increasing the Hurst coefficient in the streamflow generation model from 0.5 to 0.85 on the performance of the reservoir system are relatively small in both the high- and low-demand scenarios. The effects of combined increases in the frequency of droughts and more severe droughts (because of increases in mean monthly temperatures and decreases in mean monthly precipitation) were not examined. However, by comparing the results of the base case with Case 7, one can reasonably infer that this would reduce system reliability and increase the average annual magnitude of shortfalls in Cases 1 through 6 in the high, and possibly the low, demand scenarios.

Groundwater mining. Between 1958 and 1980 groundwater levels in SRP wells declined by about 32m. During this same period, annual groundwater pumping from these wells averaged about 432×10^6 m³/yr (Salt River Project 1981). Given the “grandfather” status of the SRP under the 1980 Arizona Groundwater Management Act, it is not clear what effect the Act will have on future groundwater pumping by SRP. To simulate voluntary compliance with the spirit of the Act, maximum monthly pumping capacity was fixed at 67.8×10^6 m³/yr, which is about 80% of the current usable capacity. The results of the simulations suggest that the amount of groundwater pumped annually will depend as much, if not more, on the future level of water demand in the project area as on the effects of climatically induced decreases in mean annual and monthly streamflow into the project reservoirs. The effect of climatic variation on groundwater supplies was not examined in the case studies. However, canal lining and the sharp reduction in irrigated acreage that is contemplated under the low-demand scenario may offset the effects that reduced pumping could have on the available supply of groundwater since less recharge would occur due to canal seepage and deep percolation of irrigation water (Long et al. 1982). In the high-demand scenario, these sources of recharge are assumed to continue; however, because the average annual pumping rate is higher than the historical average in Cases 1 through 7, water level declines would probably continue. In addition, the rate of decline in groundwater levels would probably be greater than the historical average because of reductions in recharge through reservoir spillage as streamflow decreases.

Surface water losses from storage systems. The effect of increases in temperature on surface water evaporation from SRP reservoirs is difficult to detect from Tables 3.6 and 3.7 because of the intermediate effects of changes in the exposed surface area of the reservoirs. As expected, increases in monthly mean temperatures of 1 and 2°C increased the number of

millimeters of surface water evaporation. At the same time, however, the surface area of the reservoirs was decreasing because of decreases in storage from the base case. Nevertheless, the relationship between mean monthly reservoir storage and mean annual reservoir evaporation that can be inferred from the results in Tables 3.6 and 3.7 are positive. If reservoir storage, which is a proxy for reservoir area, is held constant, it can be shown from this relationship that the volume of water lost because of surface water evaporation will increase with temperature. The effects of increased temperatures on reservoir evaporation is stronger in the low-water demand cases (Tables 3.6) than in the high-water demand cases (Table 3.7) because more of the surface area of the reservoirs is exposed to evaporation when water demands are low.

Vegetation management. Ffolliott and Thorud (1974) have estimated that intensive vegetation management practices could increase the mean annual yields of the Salt and Verde Rivers by approximately 345×10^6 and 284×10^6 m³. However, as Hibbert (1979) has pointed out, these figures represent an absolute, upper limit on recoverable precipitation. The results in Tables 3.6 and 3.7 suggest that the need to increase water yields in this fashion will largely depend on the magnitude of future demands. Under the low-demand scenario, no shortages occur in any of the seven cases. Given 1980 demands in the future, the magnitude of average annual shortfalls is relatively severe only in Cases 5 and 6. However, given the very low risks associated with these shortages, it seems unlikely that it would be economically feasible to eliminate these shortages entirely through vegetation management. Of course, substantially greater reductions in streamflow than those shown by Cases 5 and 6 would alter this conclusion.

Generalizing the case study results to other river basins is complicated by the variety that characterizes the response of hydrologic systems in different basins to climate variation and, by implication, climate change. Nevertheless, the Salt River Basin does share at least three very important characteristics with many other basins in arid regions of the world that are now experiencing rapid population growth and economic development. First, water users in these basins are primarily dependent on snowmelt-derived runoff, the source of which is extremely variable on a year-to-year basis. Second, large storage reservoirs and supplemental groundwater pumping are, in many cases, the basic means used in these basins to smooth out the potentially adverse effects of climate variability. Third, traditional patterns of water use are changing as land is converted from agricultural to urban and suburban land uses. However, despite these similarities, the Salt River Basin is somewhat special because of

a combination of intensive management and large reservoir and groundwater storage.

There are three basic conclusions that can be drawn from the case study for basins that share the characteristics described above for the Salt River. These conclusions, which apply only in the case of the admittedly one-sided (e.g., adverse) climate modifications shown in Table 3.5, are as follows: (1) even though a storage system may be characterized by a high degree of reliability, it still can be very vulnerable to adverse climate changes in the sense that the small number of shortages expected to occur are large; (2) climatically induced reductions in surface water supplies can be expected to result in increased groundwater development and pumping to make up for the decrease in surface water supplies; and (3) future projections of the effects of climate change on the balance between water supply and demand may be in great error if they fail to account for the effects of technological and institutional changes on the demand for water.

3.5 SUMMARY

The current state of knowledge about the indirect effects of CO₂ buildup in the area of water resources can be summarized by our ability to answer the following four questions: (1) how will CO₂ buildup directly and indirectly affect climate and vegetation; (2) how will CO₂-induced changes in the parameters of climate and vegetation influence the relevant physical outputs of the hydrologic system; (3) what will the pattern of future water demands look like; and (4) how will water planners, managers, and users respond to these changes over time. The knowns, uncertainties, and unknowns, in each of these areas are discussed next and are summarized in Table 3.8.

3.5.1 The Effects of CO₂ Buildup on Climate

State-of-the-art climate models provide information about the effects of CO₂ buildup on the statistical averages of annual and seasonal precipitation, temperature, and other meteorological variables over fairly large areas. The hydrologic system of a drainage basin responds continuously over time to changes in meteorological conditions, the important characteristics of which are not adequately characterized by this information. Moreover, the response of the hydrologic system in a drainage basin to changes in weather conditions is subject to variations because of differences in geologic structure and topography, vegetation cover, and soil features across space which can be measured in hundreds of meters rather than hundreds of kilometers.

Given these two mismatches, the useful information that can be obtained from climate models to conduct hydrologic investigations, even over large areas (in hydrologic terms), is limited at this time.

What we know about the effects of CO₂ buildup on climate relates principally to the direction of expected

changes in global mean temperature. Most scientists now agree that a doubling of CO₂ concentrations in the atmosphere will result in an increase in global mean surface air temperature of 1.5°–4.5°C, with amplification of warming in polar regions (MacCracken and Luther 1985). The fact that the expected increase must be

Table 3.8
Summary of Major Knowns, Uncertainties, and Unknowns Related to Characterizing the Indirect Effects of CO₂ Buildup on Global Water Resources

Problem	Knowns	Uncertainties	Unknowns
Effects of changes in atmospheric CO ₂ on climate	Direction of change in global mean temperature	Magnitude of change in global mean temperature Magnitude and direction of change in global mean precipitation Magnitude and direction of changes in mean seasonal temperatures and precipitation, by region	Effects on type, timing, intensity and duration of storms on a regional basis Effects on variability of annual and seasonal temperature and precipitation on a regional basis Effects on frequency of extreme meteorological events that influence flooding and drought risks
Effects of changes in atmospheric CO ₂ on vegetation	Physiological responses by some plants to higher CO ₂ under experimental condition where water and temperature are not limiting to growth and/or development	Effects of CO ₂ on transpiration for a large number of plants under variable soil moisture and temperature conditions	Effects of CO ₂ and changes in climate, together, on the species composition and structure of the vegetation canopy on a regional basis
Effects of CO ₂ -induced changes in climate and vegetation response on the outputs of hydrologic systems	Theoretical relationships between principal moisture and energy fluxes and state variables within hydrologic systems Effects of changes in climate and vegetation on the direction of moisture fluxes within the hydrologic system of a drainage, given a number of simplifying assumptions	Effects of changes in climate and vegetation on the magnitude and in some cases the direction of changes in moisture fluxes within the hydrologic systems of actual drainages under "realistic" conditions Types of models and related data bases best suited to accurately predict the effects of changes in climate and vegetation on the outputs of the hydrologic system of individual drainages	Effects of future changes in land-use patterns on the response of individual drainages to CO ₂ -induced changes in climate and vegetation Effects of physiological and structural changes in regional vegetation on interception storage capacity, ability of soil to retard runoff, infiltration rates and mechanical weathering of soils and the nutrient leaching action of precipitation
Predicting future demands for water	Short-run sensitivities of many different water demands to changes in temperature and precipitation Short-run sensitivities of many different water demands to changes in water prices, income, and other economic factors	Long-run (i.e., technology can change) sensitivities of all types of water demands to changes in climate, prices, income, etc.	Effects of CO ₂ on transpiration by commercial crops on a regional basis The magnitude and direction of long-run changes in exogenous variables, such as population, water prices, and income, which will influence future demands for water
Adaptation by society to the indirect effects of CO ₂ buildup on water resources systems	Statistical methods for detecting changes in the parameters of probability distributions	Parameters of true streamflow distributions are never known with complete certainty Effects of changes in climate and vegetation on parameters of streamflow distributions Rates at which these parameter values will change over time	The magnitude and direction of long-run changes in demographic, economic, and institutional forces that will influence future water demands and water resource development

defined so broadly indicates the uncertainty associated with current estimates of the magnitude of these changes. Scientists are not as certain about the direction of the change in global mean precipitation as they are about the direction of the change in global mean temperature. Estimates of the change in the global mean annual precipitation rate due to a CO₂ doubling range from -0.04 mm/dy to 0.18 mm/dy, with the most likely value falling in the 0.12–0.18 mm/dy range (Manabe and Wetherald 1980; Gates et al. 1981; Washington and Meehl 1982).

A second source of uncertainty in this area is related to the reliability of climate model projections at regional and seasonal levels. Contemporary climate models can provide estimates of the effects of CO₂ buildup on climate with a spatial resolution of a few hundred kilometers and a time step ranging from 10 to 40 min. However, regional and seasonal estimates of CO₂-induced climate changes usually are not presented at these levels of resolution. This is because many important physical processes relating to the primary energy and moisture fluxes between the Earth's surface and the atmosphere are not resolved within current climate models at these levels.

The effects of CO₂ buildup on the characteristics of storms represents a major unknown in this area. Particularly important in this regard are the effects of CO₂ buildup on the type, intensity, duration, frequency and timing of precipitation events, all of which play a critical role in determining the amount of runoff associated with a given amount of precipitation. The second major unknown in this area concerns the effects of CO₂ buildup on climate variability and on the frequency of extreme meteorological events. Information about the possible effects of CO₂ buildup on seasonal and annual variability in precipitation and temperature is needed regionally to determine the reliability and robustness of existing and proposed water supply systems. Additional information about possible changes in the frequency of extreme meteorological events also is required on a regional basis to better characterize the risks to society from flooding and drought.

3.5.2 The Effects of CO₂ Buildup on Vegetation

The vegetation canopy in a drainage basin plays a central role in regulating the principal moisture and energy fluxes between the atmosphere and the land surface. It also modifies soil structure through the addition of humus and protects the soil from the nutrient-leaching effect of precipitation. As such, any changes in the ability of the vegetation canopy to perform these functions may have important hydrologic repercussions.

What is currently known about the vegetation response to high concentrations of ambient CO₂ is based on a fairly large number of experimental studies of commercially important individual plant species. Most of these studies have been conducted under highly controlled conditions, where nutrients, soil, water, and temperature did not limit plant growth. The results of these studies suggest that an increase in the ambient concentration of CO₂ results in more vigorous plant growth; increases dry matter production, including fruit and leaf area; improves the water-use efficiency of plants (some more than others) because of partial closure of the stomata; and affects competition between plants.

Research in this area is currently in such an early stage that the distinction between what is uncertain and what is unknown is not always clear. From a hydrologic standpoint, the most important source of uncertainty is about the direction and the magnitude of the first-order effects of higher CO₂ concentrations on transpiration of a much wider range of commercially important and naturally occurring plant species. There are at least two general issues to be resolved here. First, do the effects of CO₂ associated with more vigorous plant growth offset the effects of greater stomatal closure on transpiration rates? Second, how do water and heat stress influence the net effect of higher CO₂ concentrations on transpiration rates? To answer these questions will require additional experimental studies of individual plants under variable atmospheric and soil moisture conditions.

The major unknowns in this area are related to the joint effect of changes in climate and atmospheric CO₂ on competition, succession, and selection among plant species and, ultimately, on the composition of natural ecosystems. Changes in the species composition and the structure of the vegetation canopy have the potential to influence interception losses, infiltration, evapotranspiration, and runoff. With one possible exception of a single study about the response of forest ecosystems to higher annual mean temperatures (Strain and Cure 1985), there is as yet no scientific basis for predicting the regional effects of CO₂ buildup on the hydrologically important aspects of terrestrial and aquatic plant communities. Until this information becomes available, a major gap will continue to exist in our ability to accurately characterize the effects of CO₂ buildup on a regional level.

3.5.3 Effects of Changes in Climate and Vegetation on the Outputs of Hydrologic Systems

To characterize the indirect effects of CO₂ buildup on specific water resource issues one must first determine how specific changes in climate or vegetation response

will influence the outputs of the hydrologic system relevant to the issue. For example, if the issue is flooding, then an obvious concern is the relationship between climate change and the magnitude and frequency of peak flows. The basic physical principles required to describe the effects of changes in climate and vegetation on the principal energy and moisture fluxes within hydrologic systems are generally well established. This knowledge makes it possible to characterize the structure of the hydrologic system of an idealized drainage basin functionally and then use comparative static or dynamic analysis to describe the factors that will influence the response of key moisture fluxes in the system (e.g., evaporation, transpiration, and runoff) to a change in the value of a single state variable, such as cloud density or air temperature. In some cases, certain simplifying assumptions can be imposed on key relationships within the system such that it is possible to predict the direction of specific moisture fluxes because of a change in boundary conditions.

However, the fact that enough is known about the physical principles of hydrology to characterize the structure and behavior of the hydrologic system in an abstract manner does not necessarily make it easy to characterize the sensitivity of a specific drainage basin to changes in climate and vegetation. There are two reasons for this. First, more information is generally needed to characterize the nature of the changes in climate and vegetation than is generally available. This point and its ramifications have been summarized in Sections 3.5.1 and 3.5.2. Second, the extreme variety, variability, and complexity of the processes influencing hydrologic phenomena make it difficult to generalize about the indirect effects of CO₂ buildup on different drainage basins. Given these two problems, the major uncertainties in this area involve the use of hydrologic models to convert the limited information available about changes in climate variables into changes in hydrologic variables for a specific drainage basin. In this vein, Klemes (1982) has identified two different approaches to hydrologic modeling: (1) the empirical approach, based on the use of multivariate regression models, which assumes that the underlying relationships between climate variation and the variation in relevant hydrologic variables are stable enough over time to be inferred from historical records on precipitation, temperature, streamflow, etc.; and (2) the causal approach, which employs systems-based models that attempt to mimic the dynamic mechanisms of the hydrologic system.

Empirical models are easy to apply, do not require extensive data bases, and often provide fairly reliable forecasts of hydrologic variables. However, empirical models have two major drawbacks. The first is that

the accuracy of these models in simulating the effects of changes in climate on runoff decreases as the climate conditions used in the simulations become more extreme. This can be a serious problem, as it was in the Salt River case study in which the simulated climate changes represented extreme conditions in the historical record. The second major drawback of these models is that a change in climate may invalidate not only the empirical relationships on which they are based, but also the results of the statistical tests used to determine their accuracy as forecasting tools. It is tempting to believe that the incorporation of greater physical detail into causal models will make them more immune to this problem. However, the evidence that systems-based watershed models are, as a group, more accurate than "empirical" models, or that they can be applied more successfully under a wider range of environmental conditions than those for which they were originally calibrated is not overwhelming (World Meteorological Organization [WMO] 1975; Todini and Wallis 1977; Sorooshian et al. 1982). Systems-based models are certainly more flexible than empirical models and have wider applications. Unfortunately, a great deal more data are required to calibrate the parameters of systems-based models. As a result, the availability of data can limit the application of systems-based models in many drainage basins. Furthermore, the high cost of calibrating and conducting simulations with more and more complicated models limits the size of the drainage basins in which they can be applied. Thus, there is no clearly defined basis for choosing the type of model best suited for characterizing the effects of changes in climate on the hydrologic system of individual drainage basins.

There are two major unknowns in this area: (1) the effects that changes in the physiological and structural characteristics of the vegetation canopy in a drainage basin will have on interception storage capacity, on the ability of the soil to mechanically retard runoff, on the infiltration rates and mechanical weathering of soils, and on the nutrient leaching action of precipitation; and (2) the effects that changes in future land-use patterns on hydrologic system responses will have to climate variability and climate change. These changes may be caused by factors totally unrelated to CO₂ buildup, such as overgrazing, deforestation, and floodplain encroachments that would have occurred even in the absence of CO₂ buildup. Alternatively, changes in the way a drainage basin responds to climate variability and change may be induced in some cases by the effects of CO₂ buildup on climate and vegetation. For example, Solomon et al. (U.S. DOE 1984) have shown that increases in mean annual temperatures consistent with current information regarding a CO₂ doubling can

potentially alter the composition of forests in North America and, by implication, the rest of the world as well. Changes in forest composition also may induce changes in human settlement and economic development in affected watersheds. Subsequent changes in land use would be expected to alter streamflow patterns, leading to possible additional geomorphological changes, and so on.

Both unknowns have serious ramifications. Typically, many of the characteristics of the vegetation canopy in a drainage basin do not constitute inputs to watershed models. With the exception of evapotranspiration parameters, the other important features of the vegetation canopy are assumed to be constant in the drainage basin, and model parameters are calibrated based on this assumption. This means that if any of the characteristics of the vegetation canopy in the basin change so that runoff is affected, the model parameters must be recalibrated with the new climate and streamflow data. However, regarding CO₂ buildup, the new streamflow data will not be available until after actual changes in climate and vegetation have occurred. This means that existing watershed models may not be very helpful for examining all of the possible effects of CO₂-induced changes in the structure of the vegetation canopy. An approach to watershed modeling is needed that will allow the important characteristics of the vegetation canopy to be entered in the model as state variables. The values of these variables could then be manipulated by the user to reflect information about changes in these characteristics as they become available from the Vegetation Effects Program.

3.5.4 Patterns of Future Demands for Water

There are two dimensions to the problem of predicting future demands for services provided to society by natural and manmade water resource systems. The first involves the indirect effects of CO₂ buildup on the demand for water and the second involves the effects of demographic, economic, and institutional factors on the demand for water.

Many different water uses are sensitive to changes in temperature. These include the demand for irrigation water, drinking water, and water for sanitation, as well as water needed for electricity generation and HVAC systems. In many cases the effects of climatic variation on these demands have been addressed within the framework of crop yield models, energy demand models, and reservoir operating models. These models are routinely used in planning studies and, in the case of crop yield models, large area assessments of the effects of climatic variation on crop production. The end use and areal coverage of these models is fairly

limited in most cases. However, compared with what is known about the effects of CO₂ buildup on climate and vegetation and the indirect effects of CO₂ buildup on natural water resource systems, information about the effects of climatic variation on water use is much more extensive. For example, a number of both causal and empirical models are available for use to determine how changes in temperature will affect soil water use for many different commercially important crop species (Callaway et al. 1982).

Although many demands for water are more sensitive to variations in climate than to prices and to other short-term economic factors (e.g., winter versus summer demand for electricity), over longer periods of time economic factors become much more important in relative, and sometimes absolute, terms. The assumption, embedded in the future demand scenario for the Salt River Project, that irrigated acreage will be virtually eliminated by the year 2035—largely because of higher land and water prices—illustrates this point. However, a key problem in this area is that, although there is much information about the price and income sensitivity of many different water demands in short- and moderately long-term situations, the accuracy of this information for projecting the effects of price and income changes on water demands in 50–100 yrs is highly uncertain. The reason is that during periods of this length, changes in the technology of water use can take place which will influence the sensitivity of water demands to changes in water prices and income, but which are not reflected in current estimates of the price and income elasticities of the affected demands for water.

There are two important unknowns in this area. The first relates to the effects of increases in the ambient concentration of CO₂ on the transpiration of water by commercially important plant species. Although this effect may be of secondary importance in relation to changes in the nonclimatic determinants of irrigated acreage patterns, differential increase in the efficiency of water use by crops would also affect their relative profitability in the market. However, too little is known about the differential effects of high CO₂ levels on the water-use efficiency of individual crops to determine the magnitude of these impacts on irrigation water demands. A second set of unknowns is related to the technical difficulties associated with accurately forecasting the values of so-called exogenous variables, such as the price of water, income, population, etc., which can influence the long-term demand for water. Although the capability to generate long-term forecasts for these variables does exist, the results must be treated with skepticism given the technical difficulties of modeling long-term interactions among economic, demographic,

and institutional factors necessary to produce these forecasts.

3.5.5 Societal and Institutional Response to the Indirect Effects of CO₂ Buildup

The way in which water planners, managers, and users will respond to the indirect effects of CO₂ buildup on water resources has two dimensions. The first involves the ability of society to detect any CO₂-induced changes in the relevant physical outputs of natural and manmade water resource systems. The second involves the nature of the adaptive responses that occur once (or if) these changes are detected.

Because of the random nature of many of the inputs to the hydrologic system, most, if not all, of the output of natural and manmade water resource systems are stochastic. Detecting a change in the probability distribution of a particular hydrologic output—for example, monthly streamflow—depends on (1) the nature of the true probability distribution of that output, (2) the parameters of the distribution that are of interest, (3) the extent of the variability in the true distribution, and (4) the magnitude and the rate of change in the parameters of the true probability distribution. The true probability distributions of a random variable are never known with certainty; however, statistical theory can very often provide unbiased estimators of the parameters of many different kinds of distributions. How well these estimators approximate the true parameters of a particular distribution will depend critically on the length of the historical record for a random variable. Often, the hydrologic records available today are quite short. In the Western United States many streamflow records are less than 50 years in length. Consequently, the uncertainty associated with the estimates of the parameters of these streamflow distributions is quite large. Moreover, many of the parameters of these distributions, which are of particular interest to water resource planners, are known to be either biased in small samples or are extremely sensitive to changes in sample size. Estimators of the Hurst coefficient are a good example of this (Wallis and Matalas 1970). In cases where short streamflow records are a problem and there is extensive variability in the existing historical records, as is the case on many streams in the Southwestern United States, even fairly large parameter changes (whether or not they are due to CO₂ buildup) in these distributions could be very difficult to detect because of the great uncertainties associated with current estimates of these parameters.

Inability to detect possible CO₂-induced changes in the parameters of streamflow distributions can have adverse consequences. For example, an undetected

increase in climate variability could cause an undetected decrease in the reliability of a reservoir system in an affected drainage basin. Unless the capacity of that system is very large in relation to the demand for water, as seen in the case of the Salt River, or unless the system is designed to be highly reliable over a wide range of climate states (a characteristic known as robustness), severe water shortages could occur. However, knowing that the effects of expected changes in climate on the outputs of hydrologic systems may be difficult to detect is important in and of itself because this information, along with other information about the possible effects of CO₂ buildup on water resource systems, can be incorporated into the design of future manmade systems by making them more robust and less vulnerable to climate change (Hashimoto et al. 1982a, 1982b). This illustrates the value to water resource planners of information about the uncertainties associated with the indirect effects of CO₂ buildup on water resource systems and the ability to detect these effects.

Finally, unknowns in this area are related to the ability of social scientists to predict the outcome of complex demographic, economic, and other institutional factors that will affect the way in which society can adapt to possible CO₂-induced changes in the outputs of natural and manmade water resource systems. These factors will determine not only the magnitude and structure of water demands in the future, but also the rate at which surface and groundwater supplies are developed, the availability of water-conserving technology, and the extent to which water management institutions develop more flexible and more efficient mechanisms for allocating available supplies. Some basins, like the Salt River Basin, may be relatively well equipped to handle fairly severe decreases in runoff. However, many other basins, particularly in less developed countries, may not be able to adjust smoothly to relatively small decreases in runoff. Yet, social scientists may be unable to predict when or even where this will be the case.

3.5.6 Data Needs

Table 3.9 outlines the data needs to further assess the indirect effects of CO₂ buildup on each of the nine generic water resource issues. These data needs are directed at three different potential data sources: the DOE Climate and Vegetation Effects programs and other sources outside the Carbon Dioxide Research Program.

Most of the data needs identified in Table 3.9 have been presented in fairly general, as opposed to very specific, terms. There are two reasons for this. First, the specific data needed to address a single research

objective within any one of the nine generic issues would be extremely long. Second, the data needs in the water resources area, in most cases, are tied closely to the methods selected to achieve a given research objective. In general, most of the data requirements listed in Table 3.9 are consistent with the information contained in Sections 3.3.1–3.3.9 devoted to the generic issues and Sections 3.5.1–3.5.5. Inconsistencies are largely due to the fact that there is little difference between the ideal data needed to assess the effects of CO₂-induced climate change on the response of natural hydrologic systems and the ideal data needed to determine the effects of current-day climate variability on the hydrologic response of a drainage basin. The major exception to this statement lies in the area of vegetation. Typically, the vegetation canopy in a basin is assumed to be in a steady-state condition. As such, methods have not been developed to assess the effects of long-term changes in the species composition and structure of the canopy on water resource systems. The need to develop such methods exists only when there is a possibility that the equilibrium of the vegetation canopy will be disrupted, as in the case of CO₂ buildup.

In most cases, the ideal data sets needed to simulate the effects of current variations in meteorological variables on the response of water resource systems are not

available, except in drainage basins that are highly instrumented specifically for research purposes. Nevertheless, water resource scientists and meteorologists have still been able to develop methods for taking available meteorological data and using these data to generate precipitation and temperature sequences that are consistent with observed and theoretical storm behavior (Waymire and Gupta 1981). Likewise, the data needs from the climate programs represent a desirable, but not a necessary, goal that will allow water resource scientists and planners to examine the effects of indicated changes on the response of natural and manmade water resource systems.

3.6 RECOMMENDATIONS FOR FUTURE RESEARCH

To simplify the problem of identifying research needs, the number of generic water resource issues was reduced from nine to four. Of the issues treated in Sections 3.4.1–3.4.9, the first two, surface water supply/storage and groundwater mining, can be grouped under the broad title of Water Resource Availability. The next four issues—conflicts in use, surface water losses from storage systems, vegetation management, and drought—either

Table 3.9
Data Needs for Further Analysis of the Indirect Effects of CO₂ Buildup on Global Water Resources

Climate Program	Vegetation Effects Program	Other Sources (not solely related to CO ₂)
Regional changes in the means and variances of the seasonal distributions of: daily precipitation, by type average daily temperature	Regional changes in the characteristics of the vegetation canopy that influence interception (leaf area) and evapotranspiration (leaf area and canopy resistance)	Effects of climate change on temperature-sensitive demands for water on a regional basis Explicit parameterization of vegetation characteristics in watershed models
Indications of major changes in regional storm characteristics that influence the type, intensity, and time distribution of precipitation	Explicit parameterization of vegetation characteristics in watershed models to account for effects of vegetation change on interception, evapotranspiration, soil storage, and retardation of runoff (joint with other sources)	Long-term changes in nonclimatic determinants of water demands and water supply on a regional basis Hydrogeological data for parameterization of regional aquifer system models
Indications, where possible, of changes in long-term persistence of mean annual precipitation.		Development of explicit linkages between climate and recharge in regional aquifer system models Long-term impacts of man on regional land uses affecting erosion, drainage, and flood plain development More accurate estimates of parameters (means, variances, and skewness) of streamflow distributions and more extensive streamflow records

influence or are influenced by the broader issue of water resource availability. By combining these six issues under the more general heading of Water Resource Availability, the total number of issues can be reduced to four: (1) water resource availability, (2) flooding, (3) river sedimentation, and (4) salinity problems.

3.6.1 Water Resource Availability

A principal research opportunity in this area involves greatly improving the current capability of general circulation models (GCMs) to provide reliable estimates of the direct and indirect effects of CO₂ buildup on the seasonal and of the regional availability of water resources on a global basis. The development of this capability would advance the state of the art in the field of hydrometeorological modeling. However, the time required to develop this capability may not allow the use of the results of this research to establish short- and intermediate-term research priorities related to this issue.

A second option involves the identification of critical regions that have the highest probability of being adversely affected by climatically induced decreases in the availability of surface and groundwater and then applying empirical or causal models, as appropriate, to bound the range of uncertainty associated with these changes. Development of this capability would provide information for setting short- and intermediate-term research priorities related to this issue; it would also assist decision-makers in adapting to the potential effects of a CO₂ buildup. A balanced approach, including research in both areas, is considered desirable.

3.6.1.1 GCM Development

State-of-the-art GCMs provide areally averaged information about the major elements of the water balance, including snow and soil moisture storage, surface evaporation, precipitation, and runoff. However, there are a number of serious problems connected with the use of existing models to determine the indirect effects of CO₂ buildup on the water balance at the regional and seasonal level. These problems include (1) the absence of groundwater recharge mechanisms and storage; (2) considerable simplification of the principal thermal energy and moisture couplings between the atmosphere, snow, and Earth surface (e.g., solar and terrestrial energy, precipitation, transpiration, evaporation, sublimation, sensible heat flux, etc.); (3) associated simplifications in important hydrologic processes such as infiltration and evapotranspiration; (4) the absence of orographic effects and vegetation impacts; and (5) an inappropriately large grid scale for resolving these processes.

The simplification of the hydrologic processes present within the structure of GCMs reflects the fact that the coupling of the dynamics of very detailed hydrologic systems to a dynamic model of the atmosphere would require resolution of these processes on temporal and spatial scales, which may be computationally infeasible or economically impractical. The solution to this problem has been to model only the atmosphere dynamically and to represent the Earth surface boundary by simple, parametric energy, and moisture conservation relationships. Given the adoption of this approach, regional and seasonal projections of the effects of varying atmospheric CO₂ concentrations on the components of the water balance are generally viewed to be among the most unreliable outputs of state-of-the-art GCMs.

Recommendations. Given these shortcomings, we recommend that the Climate and Indirect Effects Programs jointly undertake the following research:

1. Critically review and assess the technical, computational, and economic feasibility of methods for coupling ground and subsurface hydrologic processes to climate models.
2. Based on the findings of the review described above, initiate research to implement the preferred method, provided that the tests of computational feasibility and economic practicality are satisfied.
3. Validate the results obtained from the preferred method about the principal elements of the seasonal water balance(s) for the control climate at selected, representative sites.
4. Provide regional estimates of the seasonal water balance for groundwater storage, soil moisture, snow storage, evapotranspiration, and runoff.

Information needs. Information needs from within the Carbon Dioxide Research Program and from other sources would be established in the first step of the research, as outlined above. Site specific data bases that may be helpful in this research have been reviewed recently by the World Climate Research Program (World Climate Research Program [WCRP] 1983) for testing water balance parameterization schemes in GCMs.

3.6.1.2 Water Resource Availability in Critical Regions

The characterization of the effects of climate change on the availability of water resources is relatively new. However, the results from studies cited in this report suggest that a 1°–2°C increase in mean annual temperature, coupled with a 10% reduction in mean annual precipitation, may produce fairly large decreases in average annual runoff and streamflow in arid and

semiarid regions. The effects on groundwater recharge are not known because of the many different types of recharge mechanisms and their variety over space. Climatically induced reductions in streamflow on the order of 25–75% potentially can create large imbalances between the supply and demand for freshwater in many drainage basins (Stockton and Boggess 1979).

Current knowledge is limited about the geographic distribution of drainage basins that may be sensitive to climatically induced decreases in the availability of water resources. Identification of these critical regions and bounding the potential effects of CO₂ buildup on water resource availability in these regions are needed to establish future research priorities within the Carbon Dioxide Research Program and to assist water resource planners in responding to the problems that may be created by the increase in CO₂ concentrations.

Future research in this area must be organized to take into account the following uncertainties and unknowns: (1) information about the effects of CO₂ buildup on hydrologically relevant climate variables is currently limited, but improvements can be expected over time; (2) information about the effects of CO₂ buildup, directly and indirectly, on natural vegetation is not available at this time, and there is considerable uncertainty about the timetable for providing regional information in this area in the future; and (3) our ability to predict changes in water demand patterns over the next 50–100 years is extremely limited.

Recommendations. Within the framework of the limitations described above, the following research is recommended:

1. Develop and periodically update criteria to identify critical regions in which decreases in streamflow may create future imbalances between water supply and demand. These criteria should be based on (a) what is currently known about CO₂-induced changes in climate, (b) the current supply-demand balance, (c) projected water resource demands, and (d) available research.
2. Based on these criteria, identify critical regions around the globe that appear to have the highest probability of being adversely affected by CO₂-induced decreases in the availability of water resources. This activity would be conducted iteratively, over time, as more reliable information becomes available about the regional effects of CO₂ buildup on climate and vegetation.
3. Develop criteria for selecting a methodology to assess the indirect effects of CO₂ buildup on water resource availability in large (in size) drainage basins. These criteria should take into

account (a) application of methods for both surface and groundwater, (b) the ability of methods to characterize the effects of different sources of uncertainty on water supply estimates, (c) economy of data needs, (d) flexibility of the methods, and (e) economic feasibility of applying the alternatives to multiple drainage basins.

4. Identify the preferred methodology and conduct validation trials on a selected number of drainage basins. The validation trials would examine (a) the effects of varying the time resolution of climate input data on the accuracy of supply estimates and (b) the effect of low versus high flow conditions on the stability of model parameters.
5. Estimate the direct and indirect effects of CO₂ buildup on water resource availability in critical regions, bounding these estimates with appropriate confidence intervals to reflect identified sources of uncertainty. This activity would be conducted iteratively, over time, as more reliable information becomes available about the regional effects of CO₂ buildup on climate and vegetation.

Information needs. Data needed from the Climate and Vegetation Effects Programs will be determined, iteratively, as the reliability of available data improves. These data will depend, in part, on the methodology adopted to evaluate the indirect effects of CO₂ buildup on water resource availability. Data needed from the Climate Program most likely will be consistent with that identified previously in Table 3.8, namely, regional estimates of changes in mean daily precipitation (by type) and temperature on a seasonal basis. Some information about the possible effects of CO₂ buildup on the probability distributions of these variables will be needed to adequately characterize altered climate states. Without these data, the effect of changes in climate variability on the hydrologic response of individual river basins would be assessed parametrically.

Information needs from the Vegetation Effects Program are even more difficult to define at this time. Specific data needs will depend, first, on the selection of an appropriate method for incorporating changes in important vegetation parameters into a mathematical rainfall runoff model and, second, on the availability of data sets about the effects of higher atmospheric CO₂ on the species composition and structure of the vegetation canopy in natural ecosystems. Given that the state of the art in hydrologic modeling is not well developed in the former area, the lack of information about the effects of CO₂ buildup on the vegetation canopy does not constitute a “bottleneck” in advancing current knowledge in this area.

3.6.2 Other Issues

The remaining three issues, flooding, river sedimentation, and salinity problems, have been grouped together. Even though each of these issues is potentially sensitive to the direct and indirect effects of CO₂ buildup, research in these areas was considered less important than research in the area of water availability for one or more of the following reasons: (1) additional research is limited to an extreme degree by the availability of data about the direct and indirect effects of CO₂ buildup needed to advance current knowledge, and (2) the potentially adverse impacts of climate on the issue are generally outweighed by the effects of human activities.

3.6.2.1 Flooding

An assessment of the direct and indirect effects of CO₂ buildup on flooding is not practical at this time because floods are caused by locally isolated, extreme meteorological events. The ability to characterize the risks posed by catastrophic floods, even under current climate conditions, is limited by the length of most hydrologic records. In addition, the capability to generate storm sequences at the necessary level of spatial and temporal resolution to characterize future flood risks, using current climate models, is not adequately developed. Furthermore, inferences about the effects of CO₂ buildup on flooding cannot be drawn easily on the basis of the information that GCMs provide about mean annual runoff. This is perhaps the least accurate type of information generated by GCMs. Finally, changes in mean annual runoff are not, historically, a very good predictor of flooding in drainage basins.

Recommendations. Based on the problems described above, the climate program should explore the feasibility, using state-of-the-art climate models, to provide information about the effects of CO₂ buildup on climatic parameters that influence the frequency and magnitude of severe, flood-producing storms. Any research on the effects of possible changes in climate on natural flood risks should be deferred until there is much more evidence that flood risks will be increased materially by a CO₂ buildup and the data needed to characterize these risks become available.

3.6.2.2 River Sedimentation and Salinity

River sedimentation in particular and, to a lesser degree, salinity are both climate sensitive issues. River sedimentation is also extremely sensitive to changes in the abundance of vegetation in a drainage basin. However, the severity of these two issues generally appears to depend more on the intensity of human activity in a watershed than on climatic variation. In the case of river sedimentation, continued clearing

of the vegetation canopy in humid regions poses a potentially more severe threat to sedimentation-related problems than does the effect of CO₂-induced changes in precipitation or the structure of the vegetation canopy. The same general comment applies to salinity problems. In this case, man ruins good water by leaching it through marginal (salty) soils and then ruins good land by irrigating it with marginal (salty) water. Under these conditions, current management practices need to be altered before the effect of CO₂ buildup on salinity problems will become significant.

Recommendations. No further research is recommended in these areas until more evidence is available that river sedimentation and salinity will be significantly influenced by a CO₂-induced climate change.

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4. THE IMPACT OF CO₂-INDUCED CLIMATE CHANGE ON U.S. AGRICULTURE

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4.1 BACKGROUND

4.1.1 The Role of Agriculture

Agriculture is the foundation for human civilization, with the food and fiber from agriculture sustaining the world's population. Despite modern farming technologies, improved seed stocks, efficient transportation systems, and global communication local pockets of famine continue to exist. The continued growth in the world's population suggests that, despite the best efforts, hunger and malnutrition will be prevalent in the 21st century with or without climate change.

The U.S. economy relies heavily on agriculture, which with its related food and fiber systems, is the nation's largest industry. In 1979 its value was nearly \$500 billion (Tosterud and Jahr 1983). The United States is a primary exporter of agricultural products. These products not only play a role in feeding other parts of the world, but are also important in international trade. Yet, a great deal of the world's food supply is grown in the countries where it is consumed.

Many responsible authorities reason that science and technology will continue to provide solutions that will sustain food production at levels near the current per capita production even with a changing climate. However, Schneider (1976) counsels that ill-founded certainty is far worse than a realistic appreciation of the problems facing human survival. He notes that the crucial question is whether we can afford to be unprepared for the possibility of disaster and not whether we can prove conclusively that disaster really lies ahead.

Climate is the primary factor controlling the variability of crop yields in agriculture. Variabilities in climate, whether extreme events or seasonal variations, produce significant year-to-year variations in the food supply. Planning for future farm management alternatives and public policy programs for agriculture is difficult because of uncertainties in future climate changes.

Some environmental factors affecting agriculture are weather events of short durations such as hailstorms or a hard freeze; whereas events such as droughts or periods with above-normal rainfall may persist for days or weeks. Still others may be associated with long-term climate changes, inducing changes in the frequency of climatic occurrences important to agriculture. For example, the change in the frequency of major droughts, unseasonal freezes, flooding, temperature extremes, or climate-induced diseases in plants will increase or decrease the variabilities in agricultural production. If higher concentrations of carbon dioxide (CO₂) in the atmosphere cause significant change in temperature or in

the amount and timing of precipitation, whether gradual or rapid, agriculture will certainly be affected, and these effects may be harmful, favorable, or both and will probably differ by regions. The accompanying effects and adjustments in the food supply have the potential to affect local, regional, and national economies; societal stability; and relations among the nations of the world. A given agricultural or social structure may adjust within limits if enough time is available. If these limits are exceeded, the likelihood of serious disruptions increases.

The agricultural impacts of a CO₂-induced climate change are major issues in considering the regional climate changes that may require adjustments in the crops grown or the types of farming enterprises in an area. In some climatically marginal areas, the current agricultural production system may not be sustainable. Climate-related changes in the structure of the agricultural system will affect related businesses and industries. These effects will likely produce different agricultural infrastructures, institutions, and government programs. They will probably affect community attitudes and living standards, for example, shifts from a high-value crop to a low-value crop. A drought-tolerant crop, however, will have a considerable impact on the economy of a region. Whether the climate of a region becomes one with higher risk or becomes more benign, adjustments of the agricultural management system to the new climate will be necessary.

Climate change can induce stresses to the farm economy. These stresses may be local, regional, or national. But the changing climate may also be more favorable for the production of farm commodities. This report will address the variables relating to the impacts of climate change.

In addition to climate change there are other stresses on agriculture that result from the systems of government, commodity supply and demand, banking or credit restraints, and economic development. The economic consequences of political actions, when considered alone, often have a greater impact on agriculture than stresses imposed by climate. Of course, there are interactions between economic stresses and climate stresses affecting agriculture. These economic and political events may create favorable as well as unfavorable economic conditions. Historically, it can be shown that the short-term benefit from a political or economic action may become a disadvantage in the long term.

Although providing a discussion of the nonclimatic events affecting agriculture is not the intent of this report, a general reference to some of these events is probably helpful. Government programs that control land areas planted and/or that control prices of farm commodities can be either beneficial or harmful to

the farm economy. Market expansion or curtailments, either domestic or international, affect the financial well-being of agriculture. Obviously, foreign embargoes glut domestic supplies and depress prices. Money supply for farm credit and debt repayment introduces stress to both the farmer and the infrastructure serving the farmer.

4.1.2 Selection of the Scope of the Study

It is impossible in a single chapter to adequately characterize the climatic fluctuations and the attendant changes in agriculture that exist in the widely varying agroclimatic regions of the United States, much less the entire world. Therefore, this chapter will concentrate on the agricultural heartland in the Central United States and on the zone of moisture transition along the western margins of this region. This analysis should serve as a guide to similar surveys for other agricultural regions.

According to the U.S. Bureau of the Census (1982), seven states in the Corn Belt have 71% of the U.S. corn acreage; seven states in the Wheat Belt have 62% of the total wheat acreage; and the North Central States have 58% of the soybean acreage. Each crop has its own areas of suitability, depending on the climate, soils, and economic restraints. Climate changes in any area could have a significant impact on total U.S. agriculture and on the national economy as a whole. A larger analysis would include other important segments of the national agricultural economy, such as cotton, peanuts, and produce, to list a few.

Livestock production is an important part of American agriculture. Much of the corn and some of the soybeans produced are used as feed for cattle, hogs, and poultry. Livestock, particularly the ruminants, consume harvested forage as well as use pasture and rangeland. Changes in climate not only would affect the supply of feed for livestock, but also would directly affect livestock through their living environments and their management (husbandry).

4.1.3 Resources in Agricultural Production

Figure 4.1 is a schematic representation of how resources are used in making agricultural production possible. Early agricultural practices in North America were based on the abundance of land. If the soil deteriorated either by erosion or exhaustion of nutrients, it was abandoned in favor of new lands. This policy was effective as long as land appeared to be unlimited, and the policy favored westward migration. It was not until the latter half of the 19th century that the supply of new land was

exhausted. Although the total land area in U.S. farms has remained at about one billion acres since 1940, the number of farms has dropped about 60%. Because of improved production efficiency, the farm population decreased from 30.5 million in 1940 to 5.8 million in 1981 (Tosterud and Jahr 1983).

The development of technologies became the new frontier in agriculture. These include mechanization, chemical products, genetic selection, and transportation systems. Perhaps the greatest resource in the development of these new farming technologies was the inexpensive energy obtained from fossil fuels. Petroleum products are used in the manufacture of pesticides and fertilizers.

Genetic resources of farm crops and animals have been improved. One example is the development of hybrid corn, which rapidly replaced the open pollinated varieties in the late 1930s and early 1940s. Another is the development of semidwarf wheat varieties introduced about 1960 at the International Maize and Wheat Improvement Center in Mexico. This development is often identified as the source of the "Green Revolution."

Yet these genetic improvements would not have been effective without the development of fertilizer technology. Fertilizers are necessary to allow the new varieties to achieve their genetic potentials for high yields. Nitrogen fertilizers, manufactured chiefly from natural gas, have reduced the need to include nitrogen-fixing legumes in rotations. Weed control by chemicals (herbicides) has reduced the necessity of rotating crops in farm management.

The resource base of agriculture today is different from that of the generation prior to 1940. First, the land base is largely fixed, except that urban encroachment is decreasing the percentage of the total farm land area. Second, the cost of energy used to power machinery has risen, tripling in the 1970s. In the recent past inexpensive energy sources, along with large capital investments in farming, were used to replace labor and to overcome weather hazards to agriculture. In the medium- to long-range future, energy supply will decrease and its cost will increase.

Water is another resource limiting agricultural production. Livestock need water for growth, reproduction, and health. These uses, however, are almost inconsequential when compared with the water required for crops. Water used for livestock in the United States is about 1% of the water required for irrigation on U.S. farms (Council for Agricultural Science and Technology [CAST] 1982a). The water used in agriculture comes from the precipitation retained in surface storage or stored as soil water or in aquifers.

4.1.4 Institutional Support Bases for American Agriculture

Farmers in agriculturally developed areas are supported by a system comprised of research, education, information, finance, and farm supply. This infrastructure is shown on the left side of Figure 4.1. In the United States farm management is supported by farm-supply outlets, credit institutions, and marketing systems. This agribusiness infrastructure is not only represented by farm cooperatives and commercial sales outlets but also includes companies and corporations that mix animal feeds, manufacture fertilizers and pesticides, and sell and repair farm equipment. Most of these agribusiness organizations provide educational and/or advisory services to farmers to enable more effective use of farm products.

In most countries a research and educational system is provided to farmers at public expense. In the United States this system combines Federal and State resources for research on the development of efficient production methods. In 1980 (U.S. Department of Agriculture [USDA] 1982) the Federal Government supplied one-third and the State Experiment Stations supplied two-thirds of the more than \$1.2 billion in public support for agricultural research. This effort involved over 10,000 scientist years. Federal, State, and county funds provide centers of Cooperative Extension for adult education in virtually every U.S. county.

Federal agricultural programs have become a permanent part of the American agricultural system. Federal involvement is usually justified by Congress and the Executive Branch because agricultural products are needed for foreign trade, and because it is in

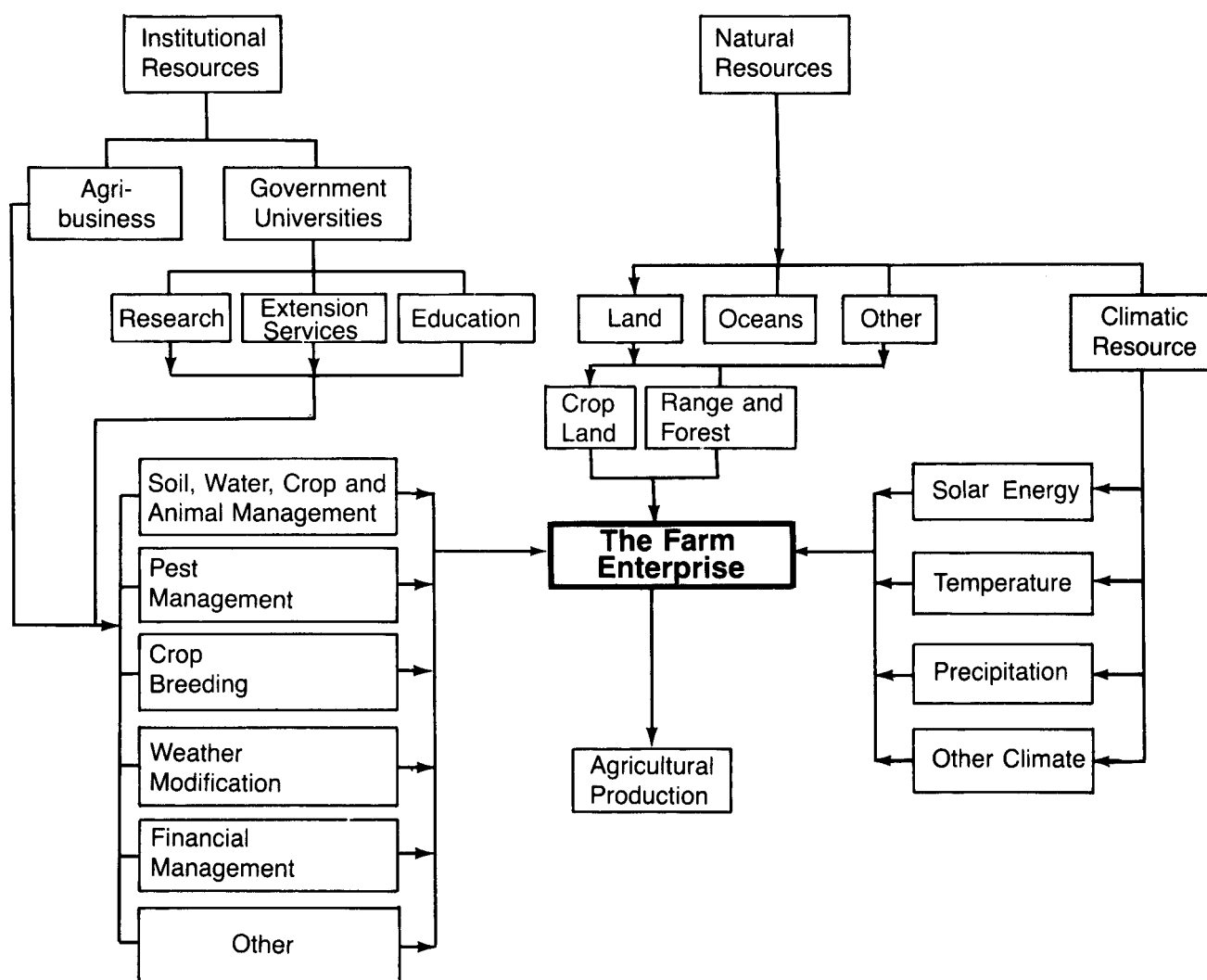


Figure 4.1. The resource and institutional support for agricultural production (adapted from National Research Council [NRC] 1975).

the public interest to supply food at reasonable costs to maintain nutritional levels. These programs include acreage allotments, price subsidies, and promotion of agricultural exports. Government programs and policies must be flexible to adapt to climate change.

4.2 CARBON DIOXIDE-INDUCED CLIMATE CHANGE AND ITS IMPACT ON AGRICULTURE

4.2.1 Climate Change and Agriculture

Agriculture is so dependent on climate that any change in climate will affect both the magnitude of production and the efficiency of the production system. The effect of increased CO₂ and other trace gas levels in the atmosphere is a general increase in temperature. Estimates of the magnitude of the expected temperature change vary among experts, but there is agreement that the temperature increase will be greater in the polar regions than in the tropics (Manabe and Wetherald 1980).

General agreement is lacking on how increased CO₂ levels will influence precipitation amounts. Manabe and Wetherald (1980) have examined the effects of doubling and quadrupling of the CO₂ content on the zonal mean values of precipitation, evaporation, and soil moisture. Their model suggests that (1) the increase in precipitation will be negligible in the lower latitudes, (2) precipitation will show a slight increase between the latitudes 15° and 35°N, (3) precipitation will actually decrease in latitudes between 37° and 47°N, and (4) there will be a substantial increase in precipitation in the higher latitudes because of the greater poleward transfer of water vapor. The evaporation rate, however, shows a rather uniform increase at all latitudes. The deficit in precipitation noted between latitudes 37° and 47°N is noteworthy, because the U.S. Corn Belt is located in this zone.

Manabe and Stouffer (1981) have simulated the CO₂-induced hydrological changes caused by a quadrupling of the CO₂ content. In spring there is a zonal belt of increased dryness centered near 45°N latitude and a region of increased soil moisture at higher latitudes. The Manabe-Stouffer model identified two separate zones of increased summer dryness, one centered about 50°N latitude and the other at higher latitudes. The earlier snowmelt, combined with increased evaporation during the summer months, results in summer dryness at the high latitudes. The summer dryness in the middle latitudes is more pronounced because of less snow accumulation and an increased evaporation rate over the high latitudes. Furthermore, the middle latitudes are likely to receive less summer rainfall because of the northward shift in the belt of maximum rainfall.

4.2.2 Trends and Climatic Risks

One of the scenarios formulated is that the CO₂-induced climate change would be gradual. As the CO₂ level stabilized a new climate equilibrium would emerge. The argument, supported by Waggoner (1984), is that under the conditions of this new climate, an adapted agricultural system would emerge. This agricultural system would reflect the economic realities of supply and demand for food and fiber. Regarding the Nation's nutritional needs and export markets it is not known whether this agricultural system would be able to fulfill the same functions as the present agricultural system. The agricultural system adapted to the new climate may or may not be better able to meet the then-existing needs of the United States.

The National Research Council [NRC] (1975) has pointed out that climate variability has a greater impact on agricultural production than does climate change. The reasoning behind this argument is that the agricultural system can adapt to the climate with low variability. When the between-year variability in weather is great, it is more difficult for the agricultural system to respond; the response in a particular year tends to be appropriate to the weather of the previous year.

Three specific factors often are not adequately considered in discussions of climate change. First is natural variability. Interannual changes ordinarily are of a much greater magnitude than either the natural or CO₂-induced climate change expected over an extended number of years. Thus, the detection of climate change over time may easily be masked by normal year-to-year variability.

Second, the existence of 20- to 22-year and 80- to 100-year patterns, as suggested by some observers, makes the evaluation of the nature and magnitude of recent climate changes difficult, much less the evaluation of the problem of predicting changes in the future. Although most models tell us that average temperatures should increase with increased CO₂ concentrations, actual temperatures have shown a downward trend during the past 40 years (MacCracken 1983). If a CO₂-induced temperature increase does in fact exist, it may consist of a gradually increasing upward displacement of these long-term patterns. As such, its existence would be difficult to detect over a short period of time.

Third, the variability of weather, both temperature and precipitation, in a given area or region is influenced primarily by the relative frequency of the location of the ridges and troughs in the circumpolar tropospheric circulation (to the layman, the location of the jet stream). Changes in regional climates due to changes in the locational frequency of the circulation patterns will, in the short term, overwhelm any gradual drift in mean

annual or seasonal temperatures. Thus, variability, as a climatic risk, is much greater for agriculture than a gradual warming of 1° to 3°C.

The climate modelers have not yet been able to evaluate the impact of a CO₂-induced climate change on climate variability that may increase the risks to agricultural production. These risks involve drought frequencies; the occurrence of lethal temperatures at both extremes; and the risks from pests, which develop under specific but unusual weather conditions. The displacement and amplitude of the atmospheric circulation patterns may produce changes in the spatial and temporal patterns of climatic risks. For a given agricultural region, the new climate may induce either greater or smaller climate risks. In mid-America, generally there has been an increase in climatic variability (year-to-year variations) since the mid-1970s (NRC 1975).

Perhaps the most critical unknown is the pattern of drought frequency. Whatever the new normal levels of rainfall in the agricultural regions of North America will be, the question is whether large negative departures from these normal levels will occur more frequently than they do at present. In arid and semiarid climates seasonal rainfall variabilities tend to be high suggesting that drought frequencies under the climate induced by a higher CO₂ content will be more frequent.

There are also questions concerning the effective length of the growing season. It is reasonable that a warmer climate will lead to an increase in the length of the frost-free period. In spring, the growing season begins when the soil is sufficiently dry for seed bed preparation and warm enough for the planted seeds to germinate. However, cool and wet springtime weather can actually hamper field operations. The questions concerning the soil water balance and the warming of the soil in spring have not been addressed by the atmosphere modelers.

Another unanswered question about the impacts of climate concerns winter temperatures in the subtropical regions. The risk of freezing temperatures in Texas, Florida, and California may be reduced under new climatic regimes induced by higher levels of atmospheric CO₂. Yet, the increasing variability of the past several years has resulted in record low temperatures in many areas and disastrous freezes in subtropical portions of the United States. This question has not been specifically addressed in the interpretation of atmospheric circulation under a new energy balance regime.

The following are other climatic risks to animal agriculture that will probably be different under a new climatic regime: (1) animal productivity (milk production, rates of weight gain) may be enhanced by warmer winters but reduced by warmer summers;

(2) higher summer temperatures may increase the mortality of adult animals from heat stress; (3) animal deaths caused by exposure of newborn animals to low temperatures may be reduced by the warmer climate or increased by greater variability; and (4) higher summer temperatures reduce the reproductive efficiencies of livestock.

4.2.3 Direct Effects of CO₂ on Agricultural Plants

Interactions exist between the direct and indirect effects of increased CO₂ concentrations on agriculture, which involve the rates of photosynthesis and respiration, water-use efficiency, and nutrient transport within the plants. Plants respond differentially to increased ambient CO₂ concentrations depending on their photosynthetic metabolic pathways. Plants are classified as C₃ (wheat, rye, barley, oats, soybean, sunflower, rice, and alfalfa); C₄ (corn, sugarcane, sorghum, and millet); and CAM type (pineapple and cacti). Most food crops belong to either the C₃ or C₄ types (Bidwell 1974).

The current concentration of CO₂ (340 parts per million by volume [ppm]) in the atmosphere is a limiting factor for photosynthesis; therefore an increase in CO₂ generally should enhance photosynthesis with the increases being especially marked for C₃ plants (Wittwer 1982; Waggoner 1984). According to Waggoner such an increase in photosynthesis is likely to result in a higher demand for fertilizers or soil nutrients.

Transpiration rates of C₃ and C₄ plants are reduced by increased levels of CO₂ because of a closure of the stomates. This decrease in the transpiration rate is more pronounced in C₄ plants. Also the water-use efficiency, defined as the ratio of photosynthesis to transpiration, should increase as a result of enhanced levels of CO₂ (Rosenberg 1981).

Studies on the effect of increased levels of CO₂ on plants are generally conducted under controlled environments, with optimal fertilization and adequate pest control. Results from studies conducted under field conditions have, however, been inconclusive (Rosenberg 1981; NRC 1983).

4.3 AREAS OF RESPONSE BY AGRICULTURE TO CHANGING CLIMATE

4.3.1 Genetic Development

Significantly, both grain yields and plant resistance to pests have increased over the past several decades. Evaluations have been made on the amount that these gains can be attributed to improved genetic quality.

For corn the rate of increase in yields from 1930 to 1980 has been a little less than 100 kg/ha/yr. After the influence of increased use of fertilizer and higher plant populations has been removed, 60–90% of the residual gains have been attributed to genetic improvement (Russell 1974; Duvick 1977, 1982). Despite such gains, a single severe drought year can drastically reduce Midwestern corn yields. Evans (1981) has noted that genetic improvements in wheat have increased yields substantially over the levels of the later 1930s. Despite these gains in yield there has been repeated concern expressed for the narrowing of the genetic base in grain crops grown in the United States and around the world (NRC 1972). For example, Zuber (1975) has reported that 29% of the hybrid seeds produced for corn used one of the three most popular inbred lines. Four years later Zuber and Darrah (1979) noted that these same three inbred lines were still the most popular and were included in 38% of the hybrid seeds produced.

The question is, How serious is the narrowing of the genetic base? Does this tendency create a crisis situation or only a concern? Duvick (1982) has presented a summary of surveys made of crop breeders of several agriculturally important crops. For corn, soybeans, sorghum, and wheat the survey showed that there are literally thousands of new varieties and hybrids in stages of advanced yield trials and hundreds of thousands of new varieties in the nursery selection stage. Under the selection system used by the seed industry in the United States, these varieties and hybrids move up the ladder from the large pool in nursery selection to the few varieties generally adopted for farm use. This selection process takes less than a decade, averaging 7 years for corn, 8 years for sorghum, and 9 years for wheat and soybeans. As the climate of a region changes, plant breeders will continue to develop new cultivars, and these varieties will be better adapted to the new climate. So long as the change is gradual, the plant breeder is likely to keep up with the forces of change introduced by climate change. To be sure, the efforts of the crop breeder will continue to provide seed with a narrow genetic base (most farms will plant the same or similar varieties). This tendency will make the farmers vulnerable to epidemics of new insect infestation and disease; however, as suggested by Duvick (1982), stress tolerance can best be achieved by introducing varieties and breeds from a diverse gene pool better adapted to the new climatic conditions.

In animal breeding there is a major effort to maintain the purity of livestock breeds (beef cattle, dairy cattle, swine, and sheep) by registering parents to ensure the purity of the breed. In the selection process, attention is given to the conformation of animal appearance to accepted standards. Under current practice, the growth

rates of young males retained for breeding stock are measured. Males with high rates of growth will transmit this characteristic to their progeny. By this technique, the efficiency of production of beef cattle and swine is increased.

It is an accepted practice to use crossbreeding to increase vigor and production rates. This practice of crossbreeding is now generally used in the beef industry in the United States.

The *Bos indicus* breeds of cattle (often called Zebu or Brahman) are more heat tolerant than the *Bos taurus* breeds. According to Tucker (1982), *B. indicus* are presently located in the United States along the Rio Grande Valley and the Mexican Gulf Coast. The *B. indicus* cattle are recognized by a humped area over the withers, a large dewlap, and large, drooping ears. This added surface area is thought to favor heat dissipation. *B. indicus* are also resistant to tropical diseases and parasites. *B. taurus* breeds do not have the added surface area and are located in more temperate regions. In the Southeast and South Central United States, cross breeds between *B. indicus* and *B. taurus*, such as Santa Gertrudis and Brangus, adapt well. Tucker believes that a warmer climate will result in a northward shift for *B. indicus* crosses (Santa Gertrudis and Brangus breeds) and that the southern limit for *B. taurus* will also shift northward.

The tropical breeds are less productive (lower milk production and reduced rates of weight gain) than the breeds adapted to temperate climates. Consequently, efforts to improve temperature tolerance may result in some reduction in productivity. Mount (1979) has stated that under cool conditions, the feed intakes and growth rates of Brahman × Friesian (Holstein) and Friesian heifers are similar. Under conditions of heat stress, however, the Brahman × Friesian cross performs better.

Forage crops are used in the agricultural system to provide feed for livestock. Although forages are used as a primary source of feed for cattle and sheep, forages also are important in swine production. Forage crops tend to be grown in the more arid regions and on marginal lands in humid regions. Thus, forage production is often vulnerable to climatic variability.

The selection of the forage used in a livestock system and the genetic improvement of the selected forage is made more complex by the following production problems: (1) some forage species do well during the cool portion of the year (cool-season grasses) and others do well at higher temperatures (warm-season grasses) (see Section 4.1.1); (2) forages are either harvested by the animal through grazing or are harvested and stored as hay or haylage (grass silage) for use as animal feed during periods of forage deficit during the year. Obviously,

the characteristics and genetic improvements will differ according to the method of harvest; and (3) grasses and legumes (clovers, alfalfa, and trefoil) are often grown in combinations to improve the nutritional value of the forage. In these cases, the ability of the legume to compete with the grass species used becomes important; this must be considered in the genetic development of both the grass and legume.

The processes of adapting and developing new varieties and strains in forage crops differ somewhat from those in grain crops. One of the differences is the priorities assigned to the allocation of resources for plant breeding between field crops and forages (political and economic considerations). It is extremely difficult to select a new forage variety from among native grasses and develop it into a proven species for a forage system. For these reasons, it requires about 20 years to bring a new forage variety into general use.¹

Currently, public agencies (U.S. Department of Agriculture and State Agricultural Experiment Stations) are moving toward leaving the development and marketing of new varieties of crops and forages to profit-oriented private enterprises—the corporations that sell seeds to farmers. This system is successful in high-volume and highly visible annuals such as grain crops. However, when this system is applied to the development and seed production of forage varieties, private seed companies are not able to respond as well. Private enterprise is, of necessity, oriented toward volume and short-term returns. The time required for selection, breeding, and testing of a new forage variety before marketing may take close to 20 years. In addition, successful seeding of a persistent perennial forage may provide animal feed for

many years, thereby reducing the annual repeat market for seed. This discourages the commercial development of forage breeding.

4.3.2 Altering Commodity Production in a Region Because of Climate Changes

With a changing climate a particular crop may become less profitable relative to alternative crops, provide a greater economic risk, or become more difficult to manage. Under such conditions farmers tend to shift to different crops, and as the climate changes there will be an evolution in the production systems. The general relationship between crops and climate is summarized in Table 4.1. The boundaries between cropping zones will change gradually with the climate. Indeed, this reaction occurs whenever there is a temporary shift in climatic patterns. Decker et al.² show that the farmers of northwest Missouri responded to shifts by increasing the area planted to sorghum in the season following a drought. Conversely, in years following above-average corn yields (no drought), they decreased the area planted with sorghum.

New crops also may be introduced into an area as the climate changes. It is very difficult to introduce totally new crops quickly because of marketing problems. For example, soybeans are well adapted to the climate of the Corn Belt, but the expansion of soybean production only occurred gradually as markets for the crop developed.

The changing climate in a region may affect animal breeds produced on a given farm. Farmers may shift to new breeds or cross breeds of the same species, or they

²W. L. Decker, V. Jones, and R. Achutuni, 1984. "A report on the Impact of CO₂ Induced Climate Change on Agriculture." Submitted to Lawrence Berkeley Laboratory, University of California, Berkeley, California, and University of Missouri-Columbia.

Table 4.1
Cropping Patterns, Climate Limitations, and Expected Changes with CO₂-Induced Climate Change

Crop Mixture	Climate Limitation	Expected Shifts With CO ₂ -Induced Climate
Corn and Soybeans	Moisture and heat stress during bloom and grain fill	Farm income from sale of grain determines crop mixture (market demand, domestic and foreign); areas of both crops shift east and north because of increased climate stress; increased CO ₂ concentration will be more beneficial to soybeans than corn
Corn and Wheat or Soybeans and Wheat	Moisture and heat stress during bloom and grain fill; the period occurs 30–60 days earlier for wheat	Historically, wheat acres determined by government allotments; wheat area likely to shift into western corn and soybean regions
Corn and Sorghum or Soybeans and Sorghum	Moisture and heat stress during bloom and grain fill; sorghum can withstand greater climate stress than can corn or soybeans	Sorghum is likely to replace corn and soybeans, to some degree, throughout the current Corn Belt; greatest replacement in Minnesota, eastern Dakotas, Nebraska, Kansas, Iowa, and Missouri

may shift to different species. Of course, farmers may use management options that allow animal production despite an adverse environment. Farmers also have options regarding the use of confinement and farm structures (buildings, wind breaks, shelters) that may become more or less desirable as the climate changes.

The Midwestern and Great Plains farmers (51% of the Nation's cattle are produced in 11 states between the Rocky Mountains and the Mississippi River) are expected to continue to produce beef cattle under a warmer climate. They will no doubt select more heat-tolerant and insect-tolerant cattle species, and the type of forage produced on these farms will change toward warm-season grasses.

4.3.3 Migration of Regions with Commodity Production

As the climate zones move, the regions of production of commodities adapted to these zones also may move. This projection assumes that soil resources for production are also adequate in these new regions. It also assumes that farmers in the new region are willing to produce the new commodity and that there are no serious marketing

constraints. To project migrations of cropping zones the crop modeler must prepare a climate change scenario involving both temperature and precipitation.

Newman (1982), for example, has estimated that the U.S. Corn Belt will shift in a southwesterly to northeasterly direction by about 175 km for every 1°C change in temperature. His analysis is based on the influence of growing season temperatures on evapotranspiration and on growing degree days during the frost-free period. The suitability of the Northeastern soils for corn production is debatable.

In another analysis Blasing and Solomon (1984) studied the effect of CO₂-induced warming and changes in the amounts and distribution of precipitation throughout the U.S. Corn Belt. Blasing and Solomon projected the shift in the Corn Belt based on four climatic scenarios. All of these scenarios called for an increase in mean monthly temperature of 3°C and an increase in mean annual precipitation of 8 cm. For the scenario exemplified by Figure 4.2 precipitation for July and August was decreased by 0.6 cm except during years with warm July temperatures. Under this model, corn production was eliminated in those climate divisions

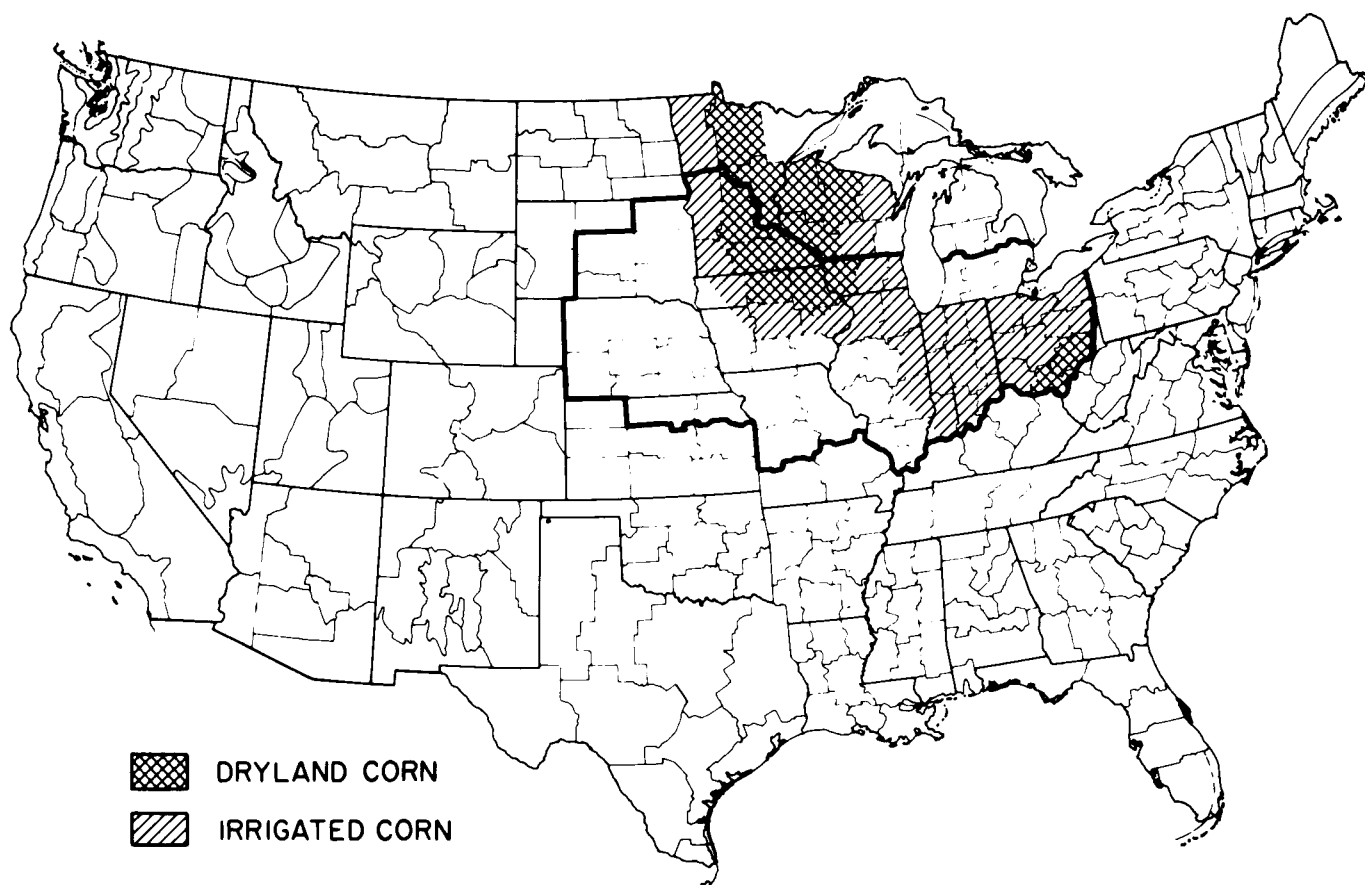


Figure 4.2. Geographic shift in the Corn Belt in response to climate warming and precipitation change. Black line outlines the current position of the Corn Belt. Source: Blasing and Solomon (1984).

with simulated July-August precipitation levels below specified amounts. The resulting shift in the Corn Belt indicates that the western half of the Corn Belt would appear to be unsuitable for corn production and only irrigated corn could be grown in the eastern half. The nonirrigated area for corn production shifted northward in response to the assumed changes in climate. It is important to consider the productivity of soils in the regions from which the migration is expected as compared with soils in the regions to which the corn production will migrate. This problem will be discussed in a later section of this chapter.

The region of wheat production should shift eastward into the current Corn Belt in response to a warmer and drier climate in the Central United States. There are often severe restrictions imposed by the Government on areas planted with wheat to control wheat production. Presumably, these restrictions will be modified to coincide with the climate change. Rosenberg (1982) presented an analysis defining shifts in the U.S. Wheat Belt because of economic considerations.

With a change toward a warmer and drier climate, sorghum should become a more important crop in the western and southern regions of the current Corn Belt. Other minor or currently unknown species may become agriculturally and nutritionally important given proper attention to their discovery, development, and use.

A warming associated with increased CO₂ levels should favor the development of cattle crosses using the *B. indicus* breeds. In addition, open-range management of cattle should be an option at locations farther north than is now possible. This would extend open-range production into the extreme northern part of the United States and into Canada. However, caution is warranted because of the continued (but less frequent) cold periods at these northern locations. The use of Zebu stocks and open-range management may be limited by chill stress during the winter season. Thus, the migration of cattle production zones may be limited by the cold winters even with a warmer climate.

A warmer climate will create many problems in maintaining the forage system to support the cattle system. Warm weather reduces forage quality and there may be an increase in the risk from pests (insects and some diseases). In the event of a shift to warmer, drier summers, warm-season grasses have advantages and their zone of production will migrate into the region now occupied by cool-season grasses.

If properly managed, warm-season grasses can fill the summertime gap in livestock grazing systems. Cool-season grasses, such as bluegrass and fescue, provide a flush of early growth but decline in production in early summer. The warm-season grasses begin to flourish in early summer and do well through June, July, and

August. As warm-season grasses drop off in productivity, fall rains and cooler weather revive the cool-season forages (Rountree et al. 1980). Warm-season grasses will have an important and as yet largely unfilled place in livestock systems, whether the climate becomes warmer and drier during the growing season, becomes more variable, or remains essentially as it is now.

4.3.4 Land and Soil Management

4.3.4.1 Soil Erosion

Tillage associated with normal agricultural practice exposes the soil surface to the dislodging action of raindrops. The dislodged soil particles are either deposited at a lower position on the landscape or carried as silt by the streams. The soil loss tolerance has been defined as the erosion rate permitting continued profitable production (typically 6600 to 11,000 kg/ha year). According to the CAST (1982b), 15.4 million ha of the 40.5 million ha of cropland in the five Corn Belt states (Ohio, Indiana, Illinois, Iowa, and Missouri) have erosion rates exceeding the soil loss tolerance.

Each soil type has an erodibility characteristic, and the amount of erosion depends on the quantity and intensity of precipitation. A changing climate will alter the risks of soil erosion from water. Whether the risk is greater or lesser under the new climatic condition depends on the expected rainfall intensities and timing of the precipitation events. Climate models do not project whether the rainfall from thunderstorms will be more or less intense in the future than it is at present. However, generalizations can be made concerning the risks of erosion from the precipitation regime of a new climate if the following interactions between climate and vegetative cover are considered.

1. For land that is continuously in summer-sown crops (corn, spring wheat, soybeans, sorghum), a wet spring and early summer will delay planting. This will leave the soil without cover during the delayed planting season and will increase the risk from water erosion if conventional tillage is used.

2. Excessively dry conditions during the warm season will result in sparse vegetative cover and increase the erosion hazard. This condition extends to overgrazed pastures and rangelands. When the drought is broken (often by heavy rains), the soil is subjected to erosion by the rainfall.

3. When management systems lead to the winter exposure of bare soil, the risk of erosion increases. Part of the increased risk comes from the action of alternate freezing and thawing, and part is caused by soil detachment and transport from late winter and early spring precipitation.

Soil erosion also occurs from wind action. Wind dislodges soil particles and transports them into the atmosphere. The amount of soil erosion from wind depends on wind speed, atmospheric turbulence, erodibility of soil, and the amount of vegetation and residue covering the ground. Woodruff and Siddoway (1965) presented computer solutions of the rates of soil loss for the Great Plains region of the United States.

Whether the altered climate will increase or decrease the potential for wind erosion depends on the frequency of high wind speeds and the seasonal distribution of high winds. Changes in surface wind characteristics cannot be estimated by these climate models. Drought frequency is also important for determining the hazards from wind erosion. Drought reduces the vegetative cover for both farm- and rangelands, and this condition leaves the soil exposed to wind action. An example of this tendency is the increased frequency of dust storms during periods of drought in the Great Plains region of the United States.

Farm management solutions for erosion (both water and wind) are well known but are sometimes too expensive for the farm enterprise to adopt without public help. These management options include contour plantings of row crops, terracing, conservation tillage (minimum and no tillage), winter cover crops, use of crop rotations, strip cropping, and windbreaks.

A significant change in soil tillage operations has occurred over the past decade. With "minimum" and "no" tillage techniques, residues are not plowed under but are mixed with surface soil. In some tillage systems, the subsoil is cultivated, leaving the surface virtually undisturbed. In extreme cases, existing vegetation is killed with chemicals and the next crop is planted with special equipment without tillage.

The primary benefits of these tillage methods are erosion control, reduction in production costs, and possibly decreased soil compaction. A primary problem requiring much study is the change in pest problems, especially weeds and plant diseases. No-till requires a higher level of management than does traditional tillage.

4.3.4.2 Soil Productivity

In the United States the highest quality soil resource is found in the areas generally associated with the western Corn Belt (northern and central Illinois, Iowa, eastern Nebraska, southern Minnesota, and southeastern South Dakota) and the Wheat Belt (the eastern half of North and South Dakota, Nebraska, most of Kansas, Oklahoma, and northern Texas). These soils have high levels of fertility and good physical properties. Soils developed under tall-grass prairies are classified in the order of Mollisols by the classification system used in the United States. They are several feet deep and contain

humus developed from the decay of deep grass roots as well as surface biomass. If the climates of these areas change, the amount of production from these soils will change because of different climatic inputs. Reduced yields would be expected from warmer growing-season temperatures and reduced rainfall.

To the east and north of the region with high-quality soils in the United States and Canada are areas with soils capable of sustaining agriculture, but they are of lesser quality. Field crops, forage crops, and specialty crops are profitably managed in these regions. The warmer climate, particularly if it is associated with an earlier summer and delayed fall freeze, will enhance the agriculture of these regions.

The Alfisol and Spodosol soils of the forest areas in the North-Central United States and central and eastern Canada were developed from the decay of surface wood and leaf litter, with humus incorporated into the top few inches by soil fauna. Thus, the three primary layers or zones (horizons) of a mature soil profile are more distinct. These soils possess a distinct "A" horizon, or upper zone, of organic matter accumulation. This zone is relatively susceptible to erosion. Once this layer is diminished or gone, few reserves are available in the subsoil to sustain agriculture.

The soils formed under hardwood forests in the southern portion of the region (Alfisols) are more productive with top soil developed to depths of 20–25 cm (8–10 inches) since the retreat of the Late Wisconsinan glaciation. This region includes southern Ontario, southeastern Michigan and western New York. With good management, these soils will sustain crops. Much of this topsoil has been lost since the establishment of agriculture in the region.

Coarser soils in the northern portion of the region (Spodosols), which formed under pine and softwood forest, may have had only 5–13 cm of a humus-rich A₁ horizon (upper subzone). Beneath this layer is a light, leached A₂ layer. These soils are found in northern Michigan, Ontario, and Quebec. Such soils are difficult to manage even for sustaining marginally profitable crops.

Displacement of the Corn Belt northward and eastward from its present location because of moisture and temperature changes, as has been suggested, would result in heavier pressure on the thinner forest-type soils. The newer nonirrigated Corn Belt area suggested by Blasing and Solomon (1984) (Figure 4.2) is in the Alfisol region. Soils of this region require careful management and may provide lower yields than do the soils of the present Corn Belt. It appears unlikely that possible climate shifts now foreseen would force corn production further northward onto the Spodosols, where the capacity for adequate and sustained production is questionable.

4.3.5 Water Management

4.3.5.1 *Water as a Limiting Factor in Agriculture*

Water is the most limiting physical factor in agricultural production. The availability of water varies with time and space and the soil's ability to store water between rainfall or irrigation. Some of these variabilities are expected and the system of farm production is adapted to respond to water deficiencies. Because arid regions are almost continuously without adequate rainfall for agricultural production, the production of row crops for food and fiber in these regions is dependent on irrigated agriculture. In other regions water deficits are smaller or occur during portions of almost every year. The agriculture of these semiarid and subhumid regions must avoid the dry periods, use water stored during wet periods, import water from other regions, or use groundwater. Other geographic regions receive adequate to abundant precipitation, but, occasionally, dry weather occurs in various seasons of the year or in occasional years. In these subhumid and humid regions, some seasons experience dry weather more frequently than other seasons. These infrequent rainfall deficit periods may be serious enough to be classified as droughts. Decker (1983) notes that extreme drought occurs in humid regions of North America about 1 year out of 12. Because of the importance of water to agriculture, the most relevant questions concerning climate change deal with the expected change in rainfall patterns and rainfall dependability.

4.3.5.2 *Agricultural Water Supply and Climatic Change*

Because water is a basic resource for everything produced by agriculture, the alteration of rainfall patterns through climate change is of great importance. How will future precipitation levels differ from those of today? The concerns of those in agriculture go beyond the expectations for changes in annual amounts of precipitation. Will the seasonal distribution of precipitation change? Will the year-to-year variability in precipitation be altered? Answers to these questions are necessary before recommendations can be made concerning the need for changes in the water management systems in response to climate change.

Although there is much uncertainty about the nature of the climate change induced by CO₂ enrichment, the evaluation of water resources for agriculture assumes a set of reasonable climatic scenarios. Under a CO₂-induced climate change with warmer climates there will be an increase in evaporative demand (both from surface evaporation and vegetative transpiration). Precipitation amounts will not be greater in the major continental crop-producing areas. Manabe and Wetherald (1980)

suggest a decrease in precipitation in the important midlatitude locations. These generalizations lead to the conclusion that water stress for agriculture will be greater under a CO₂-induced climate change. In the future, water management needs should be even greater than in the late 20th century.

4.3.5.3 *Water Management for Rainfed Agriculture*

Rainfed agriculture is, of course, farming without a supplemental water supply. Two types of farm management schemes use this water supply. First, "dryland" agriculture is practiced in arid and semiarid regions where water supply for agriculture is deficient every year. The scenarios of climate change suggested here project an expansion of the regions practicing dryland agriculture. The second water management scheme is appropriate in the humid and subhumid regions. In these regions water deficiencies are not always present, and during some seasons and years water excesses are prevalent. The farm practices appropriate for these regions are "water-managed" strategies.

In the case of rainfed agriculture the supply of water for crops must depend on precipitation as buffered by the water held in reserve by the soil matrix. The pore space in this matrix contains plant-available water, air, and unavailable bound water. Soil water is the reserve for crops between precipitation. The saturated portion of the soil profile (depths below the water table) acts as an additional buffer.

The scenario assumed for CO₂-induced climate change could be altered by increasing the water supply available by precipitation. One suggested plan for increasing precipitation is cloud seeding. The CAST (1982a, p. 18) concludes that "The uncertainty about the results that may be achieved [by cloud seeding] lead to the conclusion that cloud seeding, as a technology, is not ready for general use." Dryland farming requires the use of direct management strategies to provide water for plant use. Fallowing the land is an example of one of these practices. The land is maintained free of plants in order to accumulate rain as soil moisture. Subsequent crops then use the water that has been stored in the soil. In some areas the land is fallow every other year, but other intervals also are used. Other types of dryland farming include using hillside terraces to divert local runoff during heavy rains to lower areas on the landscape for subsequent crop use.

In humid areas in water-managed agriculture several strategies are used: (1) terracing to reduce runoff and thus add to the soil water reserve; (2) the use of organic mulches by farming systems that do not use any tillage or use minimum tillage to reduce surface evaporation; and (3) the use of implements to form ridges and furrows (often called bedding) to enhance

drainage during periods of heavy rains and to allow for the placement of seeds or seedlings into favorable moisture positions for early growth during dry periods.

Under the scenario of CO₂-induced climate change, water management will become more important to rainfed agriculture. Much of the basic research to support the expansion of water conservation is completed. Applied research for determining the most suitable management options will be necessary, and expanded extension education programs on water management will be required.

4.3.5.4 *Water Management under Irrigated Systems*

Under a scenario with a climate that is warmer and drier than the present, the need for irrigation will increase. The NRC (1983) notes that a 10% reduction in precipitation and a 1°C warming would decrease the flow of the Colorado River by 25%. Even with the present climate the amount of acreage under irrigation has increased. The CAST (1982a) shows that irrigation has increased over the past 35 years in both the semiarid and subhumid portions of the United States. As projected by the USDA (1979) irrigation will continue to be an acceptable technology to hedge against the risk of dry or droughty weather in the humid Eastern United States. Should an increase in CO₂ induce a drier climate, there are almost sure to be further increases in the areas under irrigation in the Eastern United States. The limitations to further development of irrigation will be the availability of dependable water supplies and economic factors.

For irrigation management to develop, an inexpensive and dependable water supply must be available. Water mining for irrigation and other farm uses through pumping from wells sunk into aquifers offers a means for increasing the local supply for agriculture. Unless the aquifer is replenished at the same rate as it is used, this action cannot be considered a permanent solution. The Ogallala aquifer in the High Plains of the United States is an example of an aquifer being depleted by pumping for irrigation. The High Plains Study Council (1982) presented projections showing that by the year 2020 the storage in the southern portion of the region (New Mexico, Texas, and Oklahoma) will be reduced to 35% of the 1977 water storage in the aquifer. With the decline in the Ogallala water supply, irrigation in the High Plains of the United States will not continue to increase. In Texas, a 16% decrease in irrigated area is projected by 2020. In the northern portion of the aquifer (Kansas, Nebraska, and Colorado) the depletion in 2020 will be 85% of the 1977 storage level. This rapid depletion of the aquifer in the southern portions of the region has led many to suggest that water should be diverted into the area from other watersheds (the Missouri drainage basin, for example). The diversion of water from one drainage

area to another causes conflicts between water users and may not be efficient. Desalination and water reuse are other methods suggested for improving the water supply of a region. Methods to increase water supply are expensive, and water used for irrigation must be justified against water needed in other areas. Economics may force a return to dryland agriculture.

Local water diversion is another option that may be a more economical and a less controversial response to water deficiencies. Farm ponds (small lakes) can be constructed to store water during the seasons with water excesses. This water then can be used as a supply for supplemental irrigation or for livestock and human consumption. Water drawn from running streams can also be used to alleviate water deficiencies. Most major streams have alluvial flood plains along the stream that may be protected against flood by levees. Crops grown on these lands obtain some of the required water from this shallow water table. In addition, economical irrigation systems can use water drawn from shallow wells.

Using scenarios calling for warmer and drier climates, Callaway and Decker³ simulated the demand for irrigation for a watershed in southwestern Iowa. This region was chosen because of its location on the boundary between subhumid and semiarid climates. The scenario of an average increase of 2°C, a 10% decrease in summer precipitation and a 10% increase in spring precipitation (wetter springs followed by drier summers) produced an 80% increase in the irrigation needs for the region.

In the Central and Eastern United States, water for the development of irrigation will be derived from wells, on-farm catchments, and streams. Regarding wells, the quantity and quality of water in the aquifer must be considered. Farm lakes and ponds must be designed to match the watershed supply and the area to be irrigated. Haan and Barfield (1979) and Barfield et al. (1979) presented an analysis that modeled the size of a pond for irrigating corn in Kentucky. Using the past climate of the region as an indication of the expected future variability in climate, a risk analysis was made. Under the assumptions of their model, adequate water would be available in a 10 ha storage pond to produce 40.5 ha of corn with yields of 7650 kg/ha (122 bu/acre) or higher in 80% of the years. Increasing the size of the pond will, of course, result in fewer years with water shortages. Surface storage has its greatest potential in the humid and subhumid regions because runoff occurs in most years, ensuring a water supply for the dry periods.

³J. M. Callaway and W. L. Decker, "Characterizing the Effects of Climate Change on Surface Water Supply and Supplemental Irrigation Demand in the Nishnabotna River Basin." Manuscript to be submitted to Battelle Pacific Northwest Laboratory for publication.

In some cases, the existing water supply can be extended by improving the efficiencies of the irrigation system. This action will become more important under more arid conditions. Among the irrigation systems available, those with the highest water efficiencies appear to be "trickle" irrigation and "subsurface" irrigation. There are possibilities for new and more efficient sprinkler systems. Efficiency in irrigation can be improved by the use of weather information and agricultural weather advisories.

Reducing evaporation and transpiration is another method for conserving water. Evaporation from the soil surface may be reduced by use of mulches and reduced tillage. Films or floating barriers on water surfaces will reduce evaporation from water impoundments, but this may be costly and difficult to maintain. Transpiration from crops can be reduced by antitranspirants (chemicals to reduce stomatal openings), reflectants (which decrease the absorbed solar energy), and windbreaks (to reduce wind near the surface), although none of these treatments has proved economically feasible. Water conservation occurs with the removal of unwanted vegetation and reduction of surface runoff and seepage from the soil profile. The use of furrow diking in bedded land to reduce surface runoff is increasing in some areas.

The uncertainty of adequate water supplies for irrigation raises four questions:

1. What are the economically acceptable methods for retaining surplus water on a seasonal basis for subsequent use in agricultural production?
2. What methods for water conservation are possible for irrigated and nonirrigated croplands?
3. Under what conditions is it acceptable to divert water from areas with excess water to regions that are deficient?
4. What changes in Federal and State laws are necessary for the "best" development of the Nation's water resources?

4.3.5.5 Agricultural Drainage

The Soil Conservation Service (1973) defines agricultural drainage as the removal and disposal of excess water from agricultural lands. It is estimated that about one-third of all U.S. cropland is currently drained.

Four types of technologies are used in drainage: (1) surface drainage with ditches and land reforming to remove excess surface water to prevent the formation of ponds and the penetration of water into the soil; (2) subsurface drainage to remove the water that saturates the soil pore space, which according to Luthin (1966) is accomplished by placing porous tubing or tiles at a

lower level on the landscape, beneath the surface; (3) the construction of diversions (dikes and levees) that prevent water from reaching the protected agricultural lands; and (4) pumping the excess water away from the area requiring protection. These methods are expensive and are not used unless the drainage problem is chronic.

Drainage is necessary in much of the eastern Corn Belt to prevent or alleviate waterlogging of the soil and to allow earlier planting. Drainage is also necessary to remove undesirable dissolved salts found in the soil water, because salt accumulates when lands that are somewhat alkaline are irrigated. This is a problem throughout the semiarid and arid regions of the United States where irrigation is practiced. Along seacoasts, agricultural lands are often protected or reclaimed by drainage of water or diversion of water intrusions from the sea.

Climate changes brought about by increased levels of CO₂ will probably alter the need for drainage. Higher evapotranspiration rates due to warmer temperatures along with possible decreases in precipitation in some areas should reduce the need for drainage of agricultural lands. But heavy seasonal rains, particularly in the spring and early summer, will cause drainage to continue to be a major problem in most of the current humid and subhumid regions. A portion of the new agricultural lands brought into production in the Northern United States and southern Canada, because of warmer temperatures and longer growing seasons, will probably require drainage (particularly the organic soils of this region). Should the sea level rise because of melting ice, more dikes and pumping and drainage systems will be required in the coastal regions of the United States.

4.3.6 Pest Management

4.3.6.1 Integrated Pest Management

The management of agricultural pests involves the control of insects and diseases that are injurious to crops and animals and the control of weeds in crops and forages.

Integrated Pest Management (IPM) is a strategy and means to control pest populations at a level consistent with costs and returns. It relies heavily on the use of varieties resistant to pests and on natural control factors such as the weather, the timing of biological events, and the natural enemies of the pest. IPM includes the application of pesticides, but only after careful monitoring of both pest and crop development. The optimal treatment may be to take no control action (Flint and van den Bosch 1981).

IPM has the following six basic components (modified from Haynes 1982):

1. Modeling of the crop-pest system in terms of cumulative climate data, life cycle of pest and crop, environmental response, host, and alternate hosts
2. Field monitoring of the pest for populations and life stages
3. Monitoring of the current and recent past environments (the weather)
4. Evaluation of alternative control techniques
5. An information delivery system to the farmer
6. Implementation of the preferable control techniques, as appropriate

4.3.6.2 Effects of Changing Climate on Pests

Temperature, humidity, atmospheric circulation, and other weather parameters influence pests by affecting their rate of development, distribution, migration, and adaptation.

Pest development is controlled by environmental conditions. For example, the egg of an alfalfa weevil absorbs heat energy on days when the temperature is above 9°C and marks time otherwise. When it has accumulated about 110 heat units on a 9°C base, it hatches to continue its life cycle. The notorious late blight of potato, caused by the fungus *Phytophthora infestans*, develops under cool, moist conditions (Agrios 1978). Charcoal rot (*macrophomina phasolina*), another fungal pathogen, thrives under hot, dry conditions (Sinclair 1982).

Pest distribution is controlled geographically by the environmental limitations of the pest. As the climate changes, the distribution of a pest will tend to change. For example, the southwestern corn borer spread from Mexico northward and eastward at about 30 km/y reaching three counties in southern Nebraska by the late 1940s. With cooling climate, its overwintering boundary has stabilized in central Kansas (Chippendale 1979). If the future brings a northward warming trend, one would expect the ranges of this and other temperature-limited pests to again extend to the north.

Some pests migrate along the same routes each year. Others appear to be transported by low-level atmospheric circulation. Domino et al. (1983) found that black cutworm moths were apparently carried from source areas between east Texas and western Florida to northern Missouri and Iowa in one to three nights at a considerable height (up to 1.5 km above the surface) by strong southerly winds.

Pests may have reproductive strategies that help a population adapt to a change in the environment. Also, the reservoir of potential pests may contain several that will be able to take advantage of new conditions.

In general, pest problems will change as the environmental parameters change, but the nature of that change will tend to be pest-specific. Therefore, a sophisticated level of knowledge is needed about the pest and the effects of environment on pests before dealing effectively with the changing management problems brought on by variations in climatic conditions.

Insect populations generally increase with temperature and humidity; however, some insects become inactive at higher temperatures, and some do better under dry conditions. Plant pathogens generally tend to require warm temperatures and high humidity or even free water on the leaf surface, but a few pathogens are favored by dry conditions whereas others are favored by cooler conditions.

Just as a large proportion of plants is beneficial or benign to agriculture, so the majority of insects and microorganisms are also beneficial or neutral. In a natural ecosystem, a pest rarely builds its population to a level causing excessive damage before natural controls come into operation. A change in environmental conditions may have different impacts on natural enemies of the pest than on the pest itself. This may result in more effective control or in the release of the pest population from natural control.

4.3.6.3 Effects of Changing Farming Practices on Pests

In recent years there have been shortages and sharply increasing costs for the fossil fuels that are required for tillage (a threefold increase in gasoline costs during the decade of the 1970s, according to CAST 1984). Almost simultaneously came the realization that the heavy stresses on the soil resource base, caused partly by economic pressures, were resulting in serious losses of irreplaceable topsoil by erosion. Large-scale operations, time restraints, early planting, and the use of herbicides left soil without cover or cover crops during winter. This situation gave impetus to a large-scale change in farming practices. Many farmers moved from moldboard plowing and clean tillage to what is often termed conservation tillage. Instead of being plowed under, plant residues are left on the surface as protection against wind and water erosion.

Although conservation tillage controls topsoil and moisture loss, surface trash provides a rich nursery for insects, weeds, fungal diseases, and other pathogens. Applications of herbicides are used to suppress undesired vegetative growth, but other pests are not as easily controlled. There are always some pest forms that

thrive under any climate condition. Conservation tillage requires efficient management and flexibility to cope with pest problems.

4.3.6.4 *Pest Management and Climate Change*

Weather variations within a particular climatic setting determine the vitality, population numbers, and survival of pests. IPM will continue to be important in an effective agricultural management system, with or without a climate change. Climate warming should move the regions for survival and development of pests northward without reducing the populations in the areas now affected. Under existing scenarios for climate change, IPM techniques should be even more important in the future than they are today.

Systems for monitoring climatic conditions must be improved and more widely used. If techniques of pest management are to be adapted to a changing climate, it is essential to know what the climate is and what the change is. At the day-to-day operational level, the climate data system must be in near real time and site-specific in order to know when and where problems are developing or may develop in the growing crop. Such climate data systems are currently in operation in a few states. The monitoring and data system must be sustained through time so that statistical distributions and probability estimates can be developed. Such data, along with pest monitoring, are essential for developing and validating operational predictive pest models.

Systems for monitoring developmental stages and populations of pests must quickly recognize trends, discontinuities, movements, or outbreaks of pest infestation over small or large areas. The USDA Animal and Plant Health Inspection Service has begun this effort by collecting pest reports from pilot states and inputting them into a central computer.

A much better understanding of pest dispersal, transport, and migration will require extensive research. This research should focus on the identification of the circulation patterns favoring transport and on the environmental conditions causing development in the areas into which the pest has moved.

Climate changes, variability, and changes in pest management problems tend to be even more critical for specialty and high-value crops, such as fruits and vegetables.

4.3.7 *Summary of Agricultural Responses*

Table 4.2 summarizes the responses that can be made by agriculture to reduce the risks from a changing climate. The table provides a structure for linking these responses to generic issues and shows the critical climatic factors

and the time required for response. Several topics used in this table deserve a special summary statement.

4.3.7.1 *Water Needs*

It has been said that "water is the most limiting of the natural resources" used in agricultural production. The challenge to the climate modelers is to discover whether the new climate will be drier, have increased or decreased effective moisture (the amount of precipitation minus the amount of evapotranspiration), change its year-to-year variability, or alter the seasonal distribution of precipitation.

The agriculturalist and hydrologist require these climatic projections in order to design the research and information systems necessary for the development of technologies to respond to the climate change. These technologies, which are discussed in this chapter, concern the use of irrigation in humid areas, water conservation practices, and water storage during periods with abundant rain.

4.3.7.2 *Changes in Cropping Systems*

If the climate changes, the cropping patterns also will change, as noted under issue 6 listed in Table 4.2. However, the expectation that the production areas for current crops will move into areas with similar thermal zones under the new climate is probably a gross oversimplification. Economics (prices, markets, Government subsidies) may have a greater effect on cropping patterns than does the climate. If, for example, corn, soybeans, and wheat remain the most profitable food and feed grains in North America, farmers with the most productive land will try to continue producing these grains. This tendency will keep the production of corn and soybean crops in the areas where they are now produced.

Undoubtedly a drier and warmer climate will cause changes in the cropping patterns on the boundaries between the current cropping zones, and corn and soybean production will move northward. Wheat and sorghum production will increase along western boundaries of the areas in the United States where corn is now produced. Some currently minor crops may benefit from drier conditions. New crops, such as grain amaranth, phasey bean, and jojoba may prove important in the near future if production and marketing can be developed.

4.3.7.3 *Shift to Warm-Season Grasses*

Sheep and cattle production use forages as the basic animal feed. Cool-season forages that are generally used now will become less desirable under the new climate scenario (issue 6 in Tables 4.2, and 4.3). The use of warm-season grasses, which perform better under hot

Table 4.2
Weather-Climate Impacts on the American Agricultural System
as Intensified by CO₂-Induced Climate Change

Issues or Concerns	General Climatic Elements Impacting Issue	Agriculture's Response to Climate	Required Response time
1. Stability of U.S. Farm Production	Drought frequency, unusual and unexpected climatic events (e.g., freezes, hot and cold waves, weather events favorable for major disease outbreaks)	Continued production research Agricultural-weather information systems Policy alternatives from simulations	Continuing development, i.e., response is an evolutionary process
2. Climate Change, Trends, and Variabilities	Climatic trends may either lessen hazards or be more hostile Increased climatic variability unfavorable for agriculture	More flexibility in agricultural programs Alternate strategies developed early Quicker response time to climate variabilities	Season-to-season changes in farming strategies
3. Water Availability	Drier summers increase need Higher temperatures increase water loss	Reduced tillage Irrigation Mulches (crop residues and plastic covers) Adjustment in rates of fertilizer use	Shifts in tillage equipment, installation of irrigation systems; response can be made for next season
4. Impacts of Climate Change on Physiology of Animals and Crops	Heat stress reduces the conception rate in farm animals Cold and heat stress reduce animal weight gains and feed efficiencies	Shelters and shades for animals Transfer of breeding herds to more favorable climates Construct shades and windbreaks Climate control in animal confinements	Transfer of breeding sites will occur over a number of years (perhaps a decade to respond) Response within a season or time required to construct shelters
5. Management for Control of Pests	Heat and dry weather are injurious to crops, cold and freezing temperatures damage crops New insect and disease problems in warmer climate, plus increased overwintering	Farm and water management systems Adjustments of planting dates Monitor weather to warn of potential outbreak Monitor pest populations Adopt resistant varieties to limit pest development Use appropriate chemical, biological, or cultural controls	Same-season adjustment to several years to bring new cultivars on line Response limited by the development of suitable advisories; farmers respond same season as pests develop
6. Distribution of Crops and Forages	Dry and hot weather stress Production of alternate crops may be more suited to new climate	Corn acreage decreases Sorghum acreage increases Wheat acreage increases Develop alternate crops Develop technologies to produce new crops Develop markets	Response evolves over time but shifts can be made for next season Requires 20-40 years to establish a major new crop (may be accelerated under a crisis condition)

Table 4.2 (continued)

Issues or Concerns	General Climatic Elements Impacting Issue	Agriculture's Response to Climate	Required Response time
7. Genetic Development	Stress due to drier and warmer climate	Selection of drought-tolerant lines Selection of varieties that flower at different times Selection of varieties tolerant to expected crop pests Adoption of <i>Bos indicus</i> breeds and crosses	7-9 years required for new variety, about the same period to develop and test a new animal cross
	Drier and warmer summers reduce production of current "cool season" grasses	Develop new and more drought-tolerant grass species Develop the technology for using "warm season" forages	Requires 15-20 years to develop new forage varieties Adoption of existing technology may require 2-3 years
8. Land Management	Continued risk of erosive rains and increased drought frequency	Minimum and no-till practices Contouring, terracing, and other land-forming practices Systems using vegetative cover	Response controlled by economics. Next-season response possible
	Warmer climate and longer growing season may improve the suitability of current forested regions for cropland	Clearing of present forest land for crops	One to two years to remove forest

Table 4.3
Important Issues Concerning Agricultural Production Impacted by Climate Change

Issues or Concerns	Knowns	Unknowns	Required Research
1. Stability of U.S. Farm Production	(1) U.S. farmers now supply an abundant and cheap food supply; (2) research and information infrastructure supports farm production	(1) Uncertain economies regarding credit availability; (2) political pressures to alter national farm policy; (3) uncertainty regarding support for research and extension activities	(1) Development of econometric models for evaluating impacts of changes in farm policy and foreign markets
2. Climate Change, Trends, and Variabilities	(1) Climate variability has always occurred; (2) historical data (30–100 years) exists to document climate; (3) known CO ₂ atmospheric increases; (4) cooler world climates now than 4 decades ago	(1) Is climate presently (early 1980s) warming or cooling? (2) are changes likely to occur in precipitation amounts and seasonal distributions in major agricultural regions; (3) will the between-year variability in climate change?	(1) Development of statistical tools for documenting climate change; (2) continued research on atmospheric models; (3) develop dynamic models projecting precipitation amounts that are seasonal and site specific
3. Water Availability for Agriculture	(1) Water shortages will occur with or without climate change; (2) Water excesses will continue to occur; (3) Water is and will continue to be the most limiting factor in agricultural production; (4) In many areas water supply will continue to be limited	(1) Dependability of rainfall for the next 50 years; (2) most dependable storage system for water; (3) methods for applying irrigation water efficiently; (4) the geographic regions where irrigation will be most profitable	(1) Field studies of water utilization and the economic return from irrigation; (2) simulation studies using climatic scenarios for irrigation needs
4. Impacts of Climate Change on Physiology of Crops	(1) Research base exists concerning the response of specific plants to the environment; (2) simulation models have been developed relating crop growth and yields to climate variabilities; (3) general response of plant growth to changes in CO ₂ levels	(1) How will existing models simulate the response of crops to changing CO ₂ levels on large areas? (2) precision of estimating production and yields by simulation models; (3) where improvements in simulation models can best be made	(1) Tests of the effectiveness of existing simulation models; (2) design of new simulation models that account for both changes in CO ₂ levels and climate change; (3) conduct field and growth chamber experiments to further estimate the required rate processes used in simulation models
5. Management for Control of Pests	(1) Pests will continue to plague agricultural development; (2) reduced tillage practices will increase the risks of pests; (3) combined control measures (chemical, biological, avoidance) will continue to be the most effective control; (4) careful monitoring of both pests and climate must occur to have an effective management system	(1) The extent of poleward extension of existing pests under a new climate; (2) adaptation of pests to new climatic conditions; (3) unique environmental conditions that allow the development of catastrophic pest outbreak	(1) Determining climate limitations of specific pests; (2) simulate the development of pests under new climatic scenarios; (3) investigate the migration potentials for pests; (4) improve methods for the control of pests; (5) study the interactions between nutrients in plant tissue and insect population

Table 4.3 (continued)

Issues or Concerns	Knowns	Unknowns	Required Research
6. Distribution of Crops, Animals and Forages	(1) Current cropping practices in the production area of United States and the world; (2) current demand for needed supplies of feed and food grains; (3) regions with the most productive soils	(1) Will technological development allow cropping zones to remain where they are now even through the climate changes? (2) which soils of the cooler regions can support cropping systems under a warmer climate? (3) what new crops will become important as a supply of food and feed and what minor crops may become important?	(1) Develop simulation research for appraising the impacts of migrating cropping systems; (2) develop soil water models for investigating the feasibility for the movement of crop zones; (3) develop crop protein models and use-sensitivity studies to investigate the climate impact; (4) investigate a wide range of new potential crops for drier conditions; develop the most promising new and currently minor crops for wider use
7. Genetic Development	(1) New varieties and cultivars will be developed (2) the farmers of a region will continue to use genetically similar crops; (3) infrastructure exists to support further genetic development; (4) major gene pools exist in the public sector; (5) animal crosses are available with greater tolerance to heat and climatic variability	(1) What is the climatic stress for which a crop breeder should develop a crop; (2) the extent that genetic engineering will assist with the development of new crops; (3) whether the gene pools can be expanded to include wild and foreign genetic materials	(1) Use of genetic engineering to develop stress resistant cultivars; (2) include climatic stress as a selection criteria; (3) development of genetic methods leading to a broadening of the genetic base in food crops
8. Land Management	(1) Soil erosion by water will continue to be an issue even with climate change; (2) wind erosion of the soil will likely be a greater hazard with warmer climate; (3) reduced tillage will conserve the soil	(1) Which conservation practices will be economically feasible; (2) most effective soil management practices for control of soil erosion under changing climate	(1) Soil erosivity studies for soils on which crops will be grown in the future; (2) methods for evaluating most effective land use criteria

and dry conditions, will be favored. Currently, these forages are not ready for broad distribution, and it will require up to two decades for the development of seed stocks.

4.3.7.4 *Pest Management and Climate*

Pests, particularly pathogens and insects, are very dependent on the weather. As shown in Table 4.2, a warmer climate is likely to increase many pest problems on farms in the Northern United States. The agricultural response should be through an integrated management system.

4.3.7.5 *Other Issues of Special Concern*

Tables 4.2 and 4.3 identify other important issues in dealing with climate change. For plant breeding, the current system is working well. Soil erosion will be a continuing concern. Animal production for meat, milk, and eggs will change with the climate. New crops are always an issue, but a primary hindrance to adopting a new crop will be the market, processing plants, and the need for specialized farm equipment.

Farmers and the infrastructure supporting agriculture will attempt to respond to these issues through changing the crops and the animals produced and changing farm-management options. The third column of Tables 4.2 and 4.3 lists some of these responses, most of which will be evolutionary. A new technology or cropping and animal system will be tried by the more progressive farmers and then expanded and adopted by their neighbors. For example, if in western Missouri and western Iowa sorghum becomes more profitable than corn, then the amount of acreage planted in sorghum will gradually increase, given that the necessary markets also develop. On the other hand, some of the responses will not come into place without research and development. These needs are shown in Table 4.3; however, as an example of continued developmental requirements, varieties of a crop resistant to a disease or to an insect can only be achieved through successful plant breeding to obtain resistant varieties.

It will take time for agriculturalists to develop responses to climate changes. This time response is shown in the fourth column of Table 4.2. Some changes in management and technologies can occur almost immediately, whereas others can take a decade or two to develop.

4.4 STATE OF KNOWLEDGE AND CONTINUED RESEARCH AND DEVELOPMENT NEEDS

4.4.1 Weather and Climatic Impacts on Agriculture

All sectors of the farm enterprise are sensitive to weather and climate conditions. Therefore, there is

little argument against the proposition that a change in climate will alter the way agricultural enterprises are managed and the total productivity from the agricultural system. This statement should not necessarily lead to the conclusion that the climate change will be harmful to agriculture and decrease the levels of productivity. However, when viewed from a long-term perspective, climate change introduces uncertainty.

The analysis of the impact of climate change induced by increases in CO₂ concentrations is made against the backdrop of the expectations for climate change addressed by Manabe and Wetherald (1980) and is described briefly in this chapter and discussed in detail in a companion report *Detecting the Climatic Effects of Increasing Carbon Dioxide* (MacCracken and Luther 1985). This scenario provides the expectation for warming and the associated increase in evapotranspiration. The warming will be greatest in polar latitudes and smallest in the tropics. Although the global precipitation may increase, the interiors of the continents (United States, Canada, the U.S.S.R., and People's Republic of China) may be drier than they are at present. There are some indications that the new climate will provide wetter springs in these continental locations (Manabe and Stouffer 1981). The reader is cautioned to recall that over the past 40 years there has been general global cooling, and there is no conclusive evidence that this cooling trend has ended.

Stresses other than climate trends may provide greater problems for agriculture and some of these are as follows: (1) economic circumstances that will have an impact on the agricultural system and the politically derived solutions imposed in an attempt to "fix" the system; (2) the cost and supply of fossil fuels used for farm machines and raw materials used for agricultural chemicals; and (3) the loss of agricultural lands through encroachment and erosion. This chapter does not deal with these issues, but one must maintain the broader perspective as the material is interpreted.

The sensitivity of agriculture to climate change extends from land management practices and pest control to the choice of crops and animal management. Some issues for concern in the system of agricultural production are listed in Table 4.2. The second column of this table shows how climate (particularly the expected climate change from increased levels of CO₂) has an impact on these issues. The reader is directed particularly to the first five issues, for these have the greatest impact from CO₂-induced climate change.

4.4.2 Research and Development Needs

Table 4.3 lists the eight issues that produce uncertainties for agriculture under a changing climate. These issues range from the conservation of water and soil resources

to the ability of the U.S. agricultural system to continue its responsibilities in producing food. The second column in Table 4.3 lists some of the significant knowns of these concerns, and the third column identifies the major unknowns. Some of these unknowns may be removed or alleviated through research, whereas others may need to be tolerated by the agricultural system. Important concerns that need to be researched are listed in the fourth column. Some of these research needs are more important than others.

Although the first issue in Table 4.3 is of prime importance to the agricultural sector, it is the second issue that raises the greatest range of unknowns for the impacts of climate change on agriculture. To set rational policy goals for agricultural research to deal with a changing climate, there should be greater certainty regarding direction and magnitude of climate trends and variabilities than are presently known. It is particularly critical to have estimates of changes in the amounts and seasonal distribution of precipitation. Even though the outcome in these research areas is uncertain, it is imperative to continue imaginative and innovative research in climate dynamics.

A review of the list of unknowns and research needs in Table 4.3 indicates that requirements cover a wide range of the agricultural sciences. There are good reasons for this "something-for-every-research-area" approach. Climate change and climate risks affect nearly all of the agricultural technologies, so research will be required from many disciplines. Indeed, each scientist will have his or her own priorities. From the perspectives of this report, the following five research needs are among those with the highest priority (Table 4.3).

1. The design of simulation models for crop response, which accounts for both climate change and the direct effects of increased CO₂ concentration (Concern 4).
2. The use of genetic engineering to develop stress-resistant cultivars (Concern 7).
3. Development of econometric models that evaluate the impacts of climate change on national farm policy alternatives and the development of foreign markets (Concern 1).
4. Development of soil water models for investigating the feasibility of moving cropping zones (Concern 6).
5. Simulation studies with climate scenarios for determining the need and profitability of irrigation.

For agriculture to keep ahead of the new problems created by a changing climate, it will be

necessary to maintain the existing infrastructure for research. The grand collaboration among State research agencies (largely the State Agricultural Experiment Stations), Federal researchers (Agricultural Research Service, Economic Research Service, Cooperative State Research Service) and industrial developmental activities must be continued. Carrying out research and discovering truths does not mean that the results of the research will be adapted for use on farms. There is always a time lag between the completion of basic and applied research and the emergence of new technology. Time is required for testing the technology in farm situations, which is usually followed by the adoption of the feasible technologies by progressive elements of the farm population and finally it is adopted by the general farm population.

For new farm management strategies, marketing alternatives, and scientific innovations to emerge from research, a transfer mechanism to farm use must be present. The Cooperative Extension Service, with agricultural experts in virtually every county in the United States, has primary responsibility for both field testing and the adult education required for the adoption of agricultural technologies. The new practices evolving from the agricultural and environmental research stimulated by the changing climate will require innovation in these programs for the technological transfer to farms.

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5. FISHERIES: SOME RELATIONSHIPS TO CLIMATE CHANGE AND MARINE ENVIRONMENTAL FACTORS

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5.1 INTRODUCTION: CO₂, FISHERIES, AND SOCIETY

The predicted doubling of the atmospheric carbon dioxide (CO₂) concentration by the middle of the 21st century (National Research Council [NRC] 1983) is expected to have profound effects on Earth's natural systems. This increase is forecast to have direct effects on climate, vegetation, and the global carbon cycle. These direct effects may have indirect effects on some of the natural resources that support society. This chapter discusses the potential indirect effects of increased atmospheric CO₂ on marine fisheries, emphasizing economically important species from the northeastern Pacific Ocean.

5.1.1 Organization of the Chapter

The objectives of this chapter are (1) to identify the important physical, chemical, and biological processes that contribute to the regulation of marine fisheries and to describe how these processes would probably respond to climate changes resulting from increased atmospheric CO₂; (2) to examine selected case-study fisheries and to project in greater detail how they might be affected by climate change; (3) to evaluate the present ability of fishery science to make predictions about the indirect effects of increased atmospheric CO₂; and (4) to recommend additional data and research that would help resolve the existing uncertainties.

To achieve these objectives, the chapter is divided into five major sections. The remainder of this introduction briefly discusses the relationship of marine fishery resources to human welfare. Section 5.2 describes the abiotic and biotic factors affecting fish production and characterizes the general global effects expected from a doubling of CO₂. Section 5.3 examines four fisheries from the northeastern Pacific Ocean to identify specific ways that climate change may affect these species. Factors that must be considered to extrapolate from the case studies to global fisheries are also discussed. Section 5.4 reviews the uncertainties currently associated with making fisheries projections and suggests research needed to reduce these uncertainties. The major observations are summarized in Section 5.5.

5.1.2 Conceptual Framework

The production of fish biomass in the world's oceans is governed by interactions among numerous physical, chemical, and biological processes. In addition, fishery yield is influenced by economic factors and management decisions regarding resource allocation and

conservation. All of these factors may be affected, directly or indirectly, by increases in atmospheric CO₂. The projected changes in fishery yield discussed in this chapter are related to changes in global climate, carbon cycle, and vegetation (Figure 5.1). It is important to note, however, that fish do not interact directly with the atmosphere; effects of CO₂ on fisheries will be mediated entirely through changes in physical and chemical conditions in the oceans. Furthermore, unlike the resources considered in other chapters of this report, fisheries may be significantly affected by effects of CO₂ on prey and predator populations in the oceans.

Consider the simplest sequence of effects of increased atmospheric CO₂ on fisheries. Within the tolerance limits of an organism, increased temperatures associated with increased atmospheric CO₂ will increase the rates of physiological processes and stimulate growth of marine fish species. However, fish will also be sensitive to varying degrees to changes in upper ocean turbulence and currents that are caused by changes in wind patterns in the atmosphere. In addition, fish ultimately are totally dependent for their food supplies on marine primary production (photosynthesis by free-floating plants, the phytoplankton), which also is sensitive to changes in surface water temperature, turbulence, and currents. This chapter will consider climate effects on marine primary production only as they relate to fishery production. However, marine primary production may have been a critical factor in the regulation of atmospheric CO₂ fluctuations associated with Pleistocene glaciation cycles (e.g., Broecker 1984). Thus fish production is only one of several biological processes in the ocean (including the biological deposition of calcium carbonate) linked to the CO₂ vegetation effect, the global carbon cycle, and climate change.

5.1.3 Economic Significance of Fisheries

The United States is the world's fourth largest fishing nation, after Japan, the U.S.S.R., and the Peoples Republic of China (Figure 5.2). In 1983 U.S. commercial fishermen landed 3.5 million metric tons (mt) of fish (including freshwater fish and shellfish) valued at over \$2.6 billion (National Marine Fisheries Service [NMFS] 1984). Half of this catch was used directly for food and half was used for oil, animal feed, fertilizer, or other industrial purposes. The value of this catch after processing increased to \$4.7 billion. In addition, recreational fishermen are estimated to have caught 300,000 mt of finfish in 1980, with a total financial impact of \$7.5 billion.

Fishing is also important in American international trade. The United States imported \$5.1 billion fishery

products in 1983 (NMFS 1984); only Japan imports more fish in dollar value. The United States also is the world's second largest fishery exporter in dollar value (after Canada), exporting \$1 billion worth of fishery products in 1983.

The importance of fishing to a nation may best be represented not by magnitude or value of catch, but by other economic (fraction of gross national product) or dietary (fraction of protein intake) criteria. By these criteria, fishing is much more important in some smaller nations such as the Philippines and Iceland (Figure 5.2). Globally, marine species represent about 8% of total protein and 20% of animal protein intake. As a generalization, the more developed nations have a higher per capita fish catch, value of catch, fish consumption, and percentage of total protein from marine sources than do developing nations (Holt and Vanderbilt 1980). However, developing nations derive a higher fraction of their animal protein from marine sources. Most developing nations are in the tropics, and this report does not address possible climate effects on tropical fisheries. Therefore, the United States may not be representative of the impacts of climate change on fisheries of developing nations.

The fishery effects of "El Niño," a sporadic climatic perturbation in the Pacific, may provide a worst-case

scenario for the economic impacts of climate change on fisheries. The losses to fishermen on the west coast of North America from El Niño in 1982–1983 have been estimated at \$200 to \$270 million (Pacific Fishing Partnership 1984). The losses were particularly significant for the highly regarded salmon resource. Average annual income of a salmon troller declined from \$13,000 in 1982 to \$1,300 in 1983. The salmon resource was already declining prior to El Niño and may require substantial reductions on catch allocations. However, about \$55 million per year is spent to maintain salmon hatcheries and enhance salmon runs; sport salmon fishing supports an additional \$20 million per year industry. Because of these expenditures, it is extremely difficult to close the fisheries, even if that is required for their persistence. Based on previous El Niños, declines in fisheries may persist for several years.

Other fisheries with reduced catch resulting from El Niño included tuna, shrimp, Dungeness crab, and demersal fishes. There were, however, local increases in salmon catch in British Columbia and Alaska and of albacore in California due to displacement of migration routes. El Niño has also been cited as the cause of increased catches of sardines in Chile and tuna in the western Pacific. Similarly, whatever CO₂-induced climate-fisheries interactions occur on a global scale,

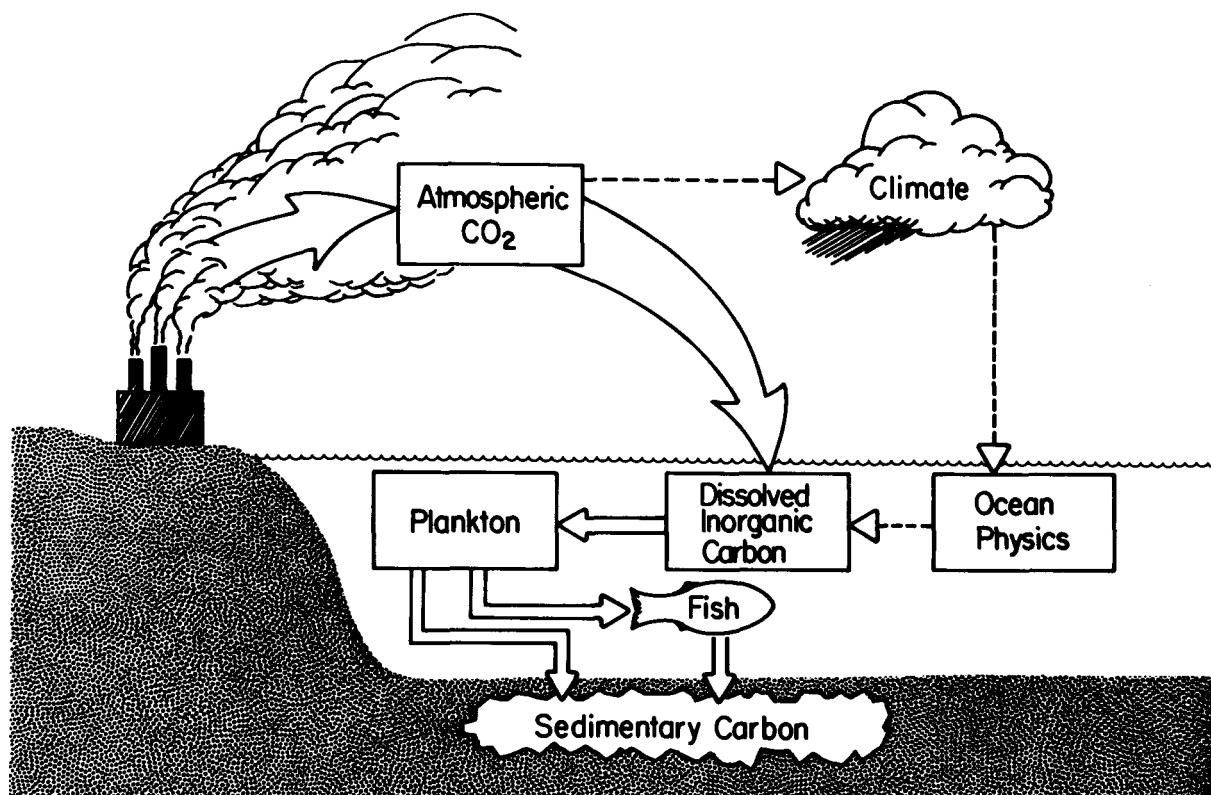


Figure 5.1. Relationship of marine fisheries to global carbon cycle and climate change.

there will be local areas or specific fisheries that display the opposite effects.

The effects of climate change on fisheries will depend on human management responses as well as on biological responses. Compared with agriculture and forestry, however, management plays only a small role in fisheries. Less than 10% of the global fish and shellfish yield involves species whose abundance is being actively enhanced by human efforts (Tont and Delistraty 1977). Management may generally be defined as the human factors involved in enhancement and regulation of the resource yield, but management of fisheries refers mainly to government catch restrictions that are designed to reduce fishing mortality (Rothschild 1981). Commercial fisheries are managed primarily by regulation of harvest, with little other deliberate human intervention. Restrictions may be on species, catch limit, types of gear used, areas or times of fishing, or on numbers or country of fishermen.

A specific example is the recent imposition of Exclusive Economic Zones within 200 nautical miles of the shores of coastal nations worldwide. Virtually all fisheries are now under national jurisdictions (Gulland 1983), and this change is generally beneficial for fishery management and conservation. Some problems remain for species that migrate to the open sea or between the economic zones of different nations, a situation that now hampers the management of salmon in the northeast Pacific. Additional problems could arise if

climate change disrupts existing geographic distributions or migration patterns.

Another factor that may interact with the effects of climate change is the increasing demand for fishery products, projected to reach nearly 100 million mt annually by the turn of the century (Robinson 1979). Such estimates are highly uncertain and depend on future trends in fuel costs, fishing technology, and marketability of new and unconventional fish resources such as krill (Rothschild 1981). The theoretical global fish yield has also been estimated to approach 100 million mt (Food and Agriculture Organization [FAO 1979]). Global catch increased 150% in the 1950s and 58% in the 1960s, but now increases only 1% or less annually. Most major fish stocks are believed to be fully exploited, and many have collapsed (Gulland 1983). Thus, under present conditions there may be a practical limit on fish yield that is equal to or lower than the global demand for fish products. It is not certain how potential global yield will be altered by climate change.

By some accounts aquaculture provides the greatest potential for increased global fish production. A decade ago it was forecast that global aquaculture yield would reach 50 million mt annually by the turn of the century, an estimate that now appears overly optimistic (Ryther 1981). Aquaculture yield is limited mainly by the area available for its application. Certain culture fisheries that are economically viable and extremely productive are freshwater species (e.g., catfish) or marine species that spawn or live entirely near shore (e.g., salmon and shellfish) (Lovell 1979). These characteristics permit either captive breeding and rearing, or a "ranching" system that rounds up adults after they have fed in the wild (Weatherley and Cogger 1977). Some experiments have been conducted with artificial fertilization of enclosed marine embayments, but fertilizing the open sea is impractical. Over the time scale of a century genetic techniques may improve greatly and may be extended to wild species, but the breeding and rearing of most wild fish stocks are not currently foreseen. Expansion of existing culture practices is limited because of conflicting uses of shoreline (including commerce, recreation, and pollution), possible negative effects on existing wild stocks, and lack of investment and research funds (NRC 1978).

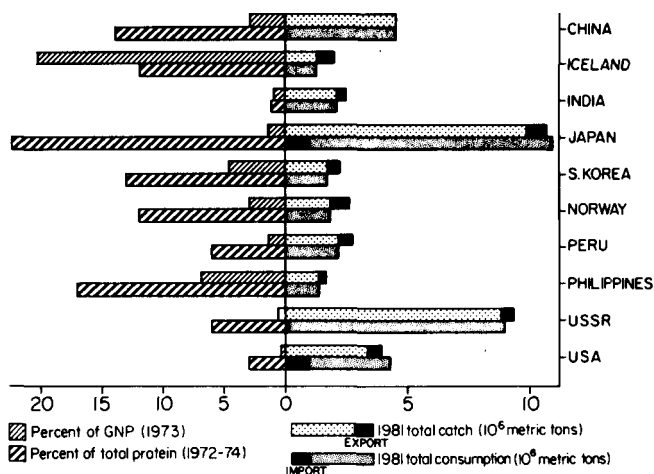


Figure 5.2. Importance of fisheries in 10 representative nations. Total consumption (food and industrial) of fishery products by each nation in million mt for the year 1981 (Food and Agriculture Organization [FAO] 1981) reflects the difference of catch plus imports minus exports. Freshwater and cultured fish and shellfish dominate the catch in China. Economic value of each nation's domestic catch is shown as a percentage of its gross national product (1973 data), and dietary importance is shown as the percentage (1972-1974 average) of fish protein in total dietary protein (data compiled by Holt and Vanderbilt 1980).

5.2 ENVIRONMENTAL FACTORS RELEVANT TO FISHERIES

This section reviews our present understanding of the environmental factors that control fishery yield and how these factors might be affected by increased atmospheric CO₂.

Fish populations in nature are one component of very complex ecosystems. Their distribution and abundance depends both on the availability of a habitat with appropriate physical and chemical characteristics and on biological interactions with numerous other species. The direct effects of CO_2 most relevant to fisheries will be changes in climate and an increase in dissolved CO_2 in seawater. These direct effects will alter the abiotic (physical and chemical) marine environment with subsequent biological impacts on fish and other species. Figure 5.3 diagrams this hierarchy of effects with major variables in each category. Table 5.1 summarizes the major ways that these variables are expected to respond to climate change on a global scale. Climate stimuli will produce multiple abiotic and biotic indirect effects, some of which may reinforce or nullify each other. It is important to recognize that in the progression from atmospheric CO_2 to fish, there is an ever-increasing uncertainty in our ability to quantify our predictions. Therefore, the following discussion is only qualitative. First we will discuss potential abiotic effects, and in Section 5.2.2 we will consider their biological consequences.

5.2.1 Abiotic Effects

Several environmental factors have been proposed as contributing to changes in fish abundance. The most frequently mentioned has been water temperature, although this may reflect the ease of measurement (Austin and Ingham 1978). Bakun and Parrish (1980) identified the most important abiotic factors for fish production on a global scale as follows: (1) water temperature, (2) vertical stability, (3) horizontal currents, and (4) sea surface convergence and divergence (associated with vertical currents). The climate variables that will produce changes in these factors are air temperature; wind speed, direction, and variability

(including incidence of storms); and the hydrologic balance (precipitation, evaporation, and freshwater addition from river runoff).

5.2.1.1 Direct Effects

An increased concentration of dissolved CO_2 in surface waters is a direct effect of increased atmospheric CO_2 that is potentially important to fisheries. Atmospheric CO_2 dissolves in water to form hydrated $\text{CO}_2(\text{g})$ and carbonic acid (H_2CO_3). The H_2CO_3 then dissociates to form bicarbonate and carbonate ions. Bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions account for approximately 98% of the inorganic carbon in seawater and act as powerful buffering agents to prevent changes in pH.

The effects of increased atmospheric CO_2 on the carbonate system of surface waters are well established theoretically (Holland 1978; Stumm and Morgan 1981; Baes 1982; Brewer 1983). The equilibrium concentration of carbon dioxide gas [$\text{CO}_2(\text{g})$] in solution will increase proportionately to the atmospheric increase. The relative concentrations of different carbon compounds in seawater are determined by chemical equilibrium constants that are well established (Millero 1979) and by biological processes that selectively remove specific carbon compounds. For example, photosynthesis by marine phytoplankton and macroalgae uses $\text{CO}_2(\text{g})$ and perhaps bicarbonate ion (Borowitzka and Larkum 1976), and precipitation of carbonate solids consumes carbonate ions. Biological reactions perturb the chemical equilibrium, which can only be restored within the kinetic restraints of the chemical system. Although surface waters are not always in equilibrium with atmospheric CO_2 , we can use equilibrium arguments to evaluate the general effects expected from increased CO_2 .

Because the dissociation of carbonic acid produced by the dissolution of CO_2 in seawater releases H^+ ions, the pH of those waters will decrease. The magnitude of this decrease can be predicted quite precisely from chemical thermodynamic constants if the alkalinity of the system remains constant (Brewer 1983). The decrease depends on the buffering capacity of the solution (Takahashi et al. 1980) and interactions with solid surfaces. As pH decreases, more materials are solubilized from solid surfaces, and buffering capacity increases. Therefore, additional change in pH is restricted. It is generally agreed that doubling atmospheric CO_2 will decrease the equilibrium pH of seawater by approximately 0.3 pH units.

Because pH is such an important chemical parameter in aquatic ecosystems, changes in pH will affect other chemical parameters and processes. In particular, it will affect adsorption and ion exchange

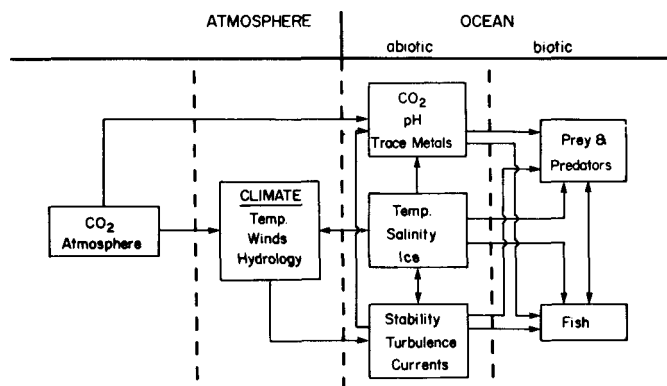


Figure 5.3. Major pathways of environmental influences on fisheries.

Table 5.1
Some Potential Abiotic Effects of Global Warming on the Ocean,
Their Biotic Consequences and Projected Effects on Fisheries

Climate-Related Abiotic Effects ^a	Biotic Effects ^b	Projected Effects on Fisheries ^b
1. Increased mean water temperature	Increased growth and development rates and metabolic demands of all species. Poleward and seasonal shifts in productivity and predator/prey distributions.	Increased survival and yield, subject to changes in predator/prey abundance. Poleward shifts of ranges and migration patterns, subject to suitable habitat.
2. Increased vertical stability at surface due to warming	Turbulent (e.g., subpolar) waters: increased photosynthesis due to retention of phytoplankton near surface. Stratified (e.g., subtropical) waters: decreased photosynthesis due to decreased diffusive nutrient supply. Earlier spring production, increased plankton patchiness.	Increased potential yield due to increased food supply. Decreased potential yield due to decreased food supply. Changes in feeding ability of fish and predators; net effect on yield uncertain.
3. Decreased latitudinal and seasonal sea ice extent	Decreased surface stability; lower intensity but greater duration of primary production.	Increased survival due to increased food supply; modified by effects on feeding ability and distribution of predators.
4. Weakening and poleward and seasonal shifts in storm tracks and surface turbulence	Areas of decreased storminess and turbulence: as in (2) above. Areas of increased storminess and turbulence: opposite of (2) above.	Same as (2) above Opposite of (2) above
5. Weakening poleward and seasonal shifts in wind-driven surface currents and coastal upwelling	Poleward and seasonal shifts in primary production patterns, depending on orientation of coastline.	Increased potential yield if food supply increases; lower yield if food decreases. Increased survival of eggs and larvae if drift loss from nursery areas decreases; decreased survival if drift loss increases.
6. Temperate decrease and high-latitude increase in net precipitation and runoff	Poleward species shifts due to poleward shifts in salinity patterns. Increased net precipitation: as in (2) above Decreased precipitation: opposite (2) above.	Local effects on survival affected by drift loss changes due to runoff, as in (5) above. Same as (2) above. Opposite (2) above.

Note. These represent *partial* relationships between generic fisheries and the abiotic and biotic environment. Interactions between these effects are considered unknown.

^aZonally averaged data (NRC 1983). Topography, runoff, and other regional factors will determine specific local impacts.

^bNeglects second-order complications such as possible changes in species of prey or predators, or changes in relative pelagic/benthic partitioning of food web. Such factors will be important locally.

processes that control the concentration of essential elements and toxic trace metals. Stumm and Morgan (1981) predicted that for each doubling of H^+ and decrease of 0.3 pH units, the free ion concentration for metals will increase by a factor of 1–2.

5.2.1.2 Indirect Effects

The interactions between climate change and the important abiotic parameters that affect fisheries are diagrammed in greater detail in Figure 5.4. The major indirect effect of climate warming will be an increase in water temperature, with a generally greater increase at higher latitudes (NRC 1983). The exact temperature increase will depend on patterns of turbulence and currents that determine vertical and horizontal heat transport.

Surface seawater temperatures at high latitudes are closely related to the extent of ice cover, which is projected to decrease as a result of warming (NRC 1983). Ice extent depends not only on air and water temperatures, but also on salinity, which depresses the freezing point of seawater to about -1.8°C . The presence of sea ice has further abiotic effects. Sea ice has very low salinity, and as seawater freezes, most of its salt remains in the water just below the ice interface. The resulting increase in the density of this layer induces convective overturn of the water column, which creates a uniform vertical temperature distribution and retards further freezing, but rapidly cools water to great depths. Furthermore, the physical barrier of surface ice cover reduces heat and momentum transfer between the atmosphere and the ocean, and snow cover on the ice greatly increases the surface albedo. When the ice

melts, the low salinity meltwater is very buoyant and remains at the surface. If it is not dispersed, it forms a very stable brackish layer that continues to insulate deeper water from heat and momentum transfer.

Surface salinity also will be affected by changes in the hydrologic cycle. Salinity will increase where net evaporation increases and will decrease where net precipitation and freshwater addition increase. Because net precipitation and runoff are projected to increase at high and low latitudes and to decrease in midlatitudes (NRC 1983), salinity generally is expected to increase at temperate latitudes and decrease at tropical and subpolar to polar latitudes. Greater changes may occur near major river mouths.

The distributions of temperature and salinity in the upper layers of the sea, together with forcing by winds and freshwater addition, have secondary effects on water motion. These motions may be separated into turbulence, which lacks net direction, and currents. Turbulent motions include surface wave action and horizontal and vertical eddies on a range of different scales. Turbulence induced either by wind stress or by the interaction of currents with the ocean bottom, shore, or other currents is often the dominant vertical motion. Currents (including tidal currents) are the dominant horizontal motions, but long-period internal waves also transport water. Convergence and divergence are special cases of horizontal motion associated with directed vertical transport (upwelling and downwelling) and sometimes become more important than turbulence.

Stability refers to the capacity of the water column to resist vertical perturbations associated with vertical mixing. Stability results from the increase of water density with depth. In natural waters stable density stratification results from increased temperature and/or decreased salinity in the surface waters. The greater the vertical density gradient, the more resistance this layer offers to forces (principally wind stress) that induce turbulent mixing within the layer and between this layer and deeper waters. Stratification tends to be self-reinforcing, because surface water warms more rapidly under reduced mixing. Commonly, surface turbulence creates homogeneous conditions to a depth at which there is a sharp increase in density. This sharp gradient is referred to as the “pycnocline,” and the associated gradients in temperature and salinity are referred to as the “thermocline” and “halocline,” respectively. The turbulent surface layer is called the “mixed layer”; in the northeastern Pacific its depth ranges from as little as 10–20 m in summer to 75–100 m in winter.

The existing global and seasonal distribution of mixed-layer depths reflects a balance between wind-induced turbulence and stability produced by warming and freshwater input. Temperature has the dominant

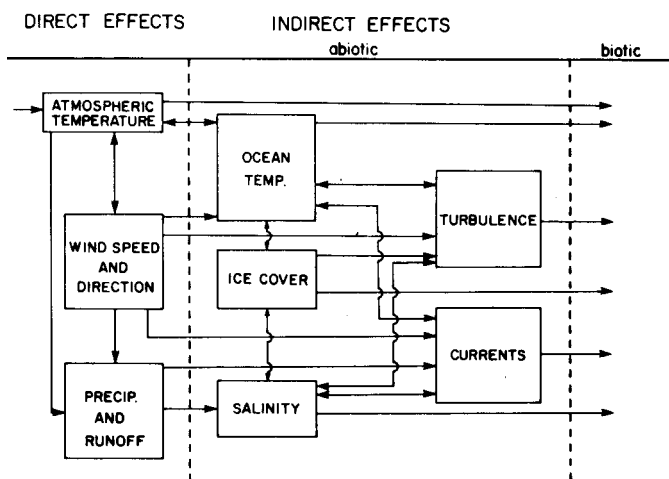


Figure 5.4. Major climatic pathways affecting the abiotic environment of fishes. Increased atmospheric CO_2 directly affects climate and dissolved CO_2 . CO_2 indirectly affects seawater temperature, salinity, ice cover, turbulence, and currents. All of these abiotic effects have biotic consequences.

effect on seawater density except at relatively low temperatures ($<5^{\circ}\text{C}$) and near large freshwater sources. Thus, stability tends to decrease and turbulence to increase at higher latitudes, especially along the paths of prevailing winds and storm tracks. Exceptions to this trend are found where rivers and ice melt provide localized freshwater sources that produce high stability. Climate warming will tend to increase stability and decrease turbulence, except where strong freshwater sources are reduced or in regions experiencing a net increase in prevailing winds or storms.

Horizontal currents are generated both by wind stress and by lateral pressure gradients resulting from temperature and salinity distributions. Freshwater addition also can drive currents, both directly by entrainment and indirectly by creating density gradients. Water transport, in turn, alters temperature and salinity distributions so that major ocean currents represent a long-term equilibrium with mean hydrographic and climate conditions on which smaller interannual, seasonal, and meteorological variabilities are superimposed. Vertical currents result from convergence or divergence of surface water caused by the Coriolis effect acting on areas between opposing currents or along shorelines. Convergence is characterized by an elevated sea surface and downward water transport (downwelling), and divergence by a depressed sea surface and upward transport (upwelling). These vertical currents are several orders of magnitude slower than most horizontal currents (10^{-2} – 10^{-3} cm s^{-1} compared with 1 – 100 cm s^{-1}), but they have important effects on surface temperatures and salinities and on organisms.

Although local changes in temperature and salinity distributions may modify current patterns under a climate-warming scenario, the major potential changes in currents would result from changes in wind speed and direction. If latitudinal atmospheric temperature gradients are reduced by greater warming at higher latitudes, winds and currents in general should weaken. Latitudinal shifts in wind patterns could cause corresponding shifts in current patterns. Global generalizations are difficult to make, however, because local surface wind and current patterns are significantly influenced by local terrestrial and submarine topography. For example, several upwelling zones exist because of the coincidence of properly oriented winds and coastline, and it cannot be assumed that, after a shift in wind patterns, such a coincidence will persist.

5.2.2 Biotic Effects

The important biological processes affecting fish production and the abiotic factors that may alter each of these processes are diagrammed in Figure 5.5. The

abiotic effects discussed in Section 5.2.1 affect virtually all marine organisms, although these effects may differ, depending on habitat, trophic level, and other ecological factors. The important abiotic factors are those that regulate production, growth, and survival rates of fish eggs, larvae, and juveniles. These factors may influence fish directly or by affecting the abundance, spatial and temporal distributions, and condition of prey, competitors, predators, and disease and parasite organisms. Thus, each climate factor has multiple interacting impacts on fish and their environment. Some of these individual mechanisms are well understood and others are not, but there is little knowledge of the net impacts of interactions among these factors.

5.2.2.1 Effects of pH

Bland et al. (1982) reviewed the direct effects of increased CO_2 concentrations on aquatic biota. Neither increased concentrations of $\text{CO}_2(\text{g})$ nor changes in the carbonate chemistry of seawater are expected to affect fish directly. The major direct effects on marine biota from changes in carbonate chemistry are expected to be changes in phytoplankton production and community structure and decreased biosynthesis of calcium carbonate (CaCO_3).

The rate of photosynthesis may be expected to increase because of increased availability of $\text{CO}_2(\text{g})$ (Holm-Hansen 1982). Wetzel et al. (1983) predicted that the effects in seawater will be less than in freshwater environments because of the high carbonate concentrations in seawater and the low concentrations of other essential nutrients such as nitrogen and phosphate. Because photorespiration decreases as the ratio of CO_2 to O_2 increases, it is expected to decrease with increased levels of atmospheric CO_2 . Therefore, for a given level of primary production, more photosynthate should be produced and higher quantities of phytoplankton biomass should be available for consumption by higher trophic levels.

Total production is generally considered to be limited by nutrients or solar irradiation and therefore may not change significantly. However, even if total production remains constant, the timing and magnitude of daily production and the species composition of plankton assemblages may change. This is important for higher trophic levels because plankton species vary in quality as fish food. Because the total production of fish is determined by the magnitude of primary production and food-web interactions (Gulland 1970), changes in community structure may have profound effects on fish production, although there is little information to evaluate such effects.

The biogenic synthesis of CaCO_3 is a major mechanism for removing CO_2 from surface waters

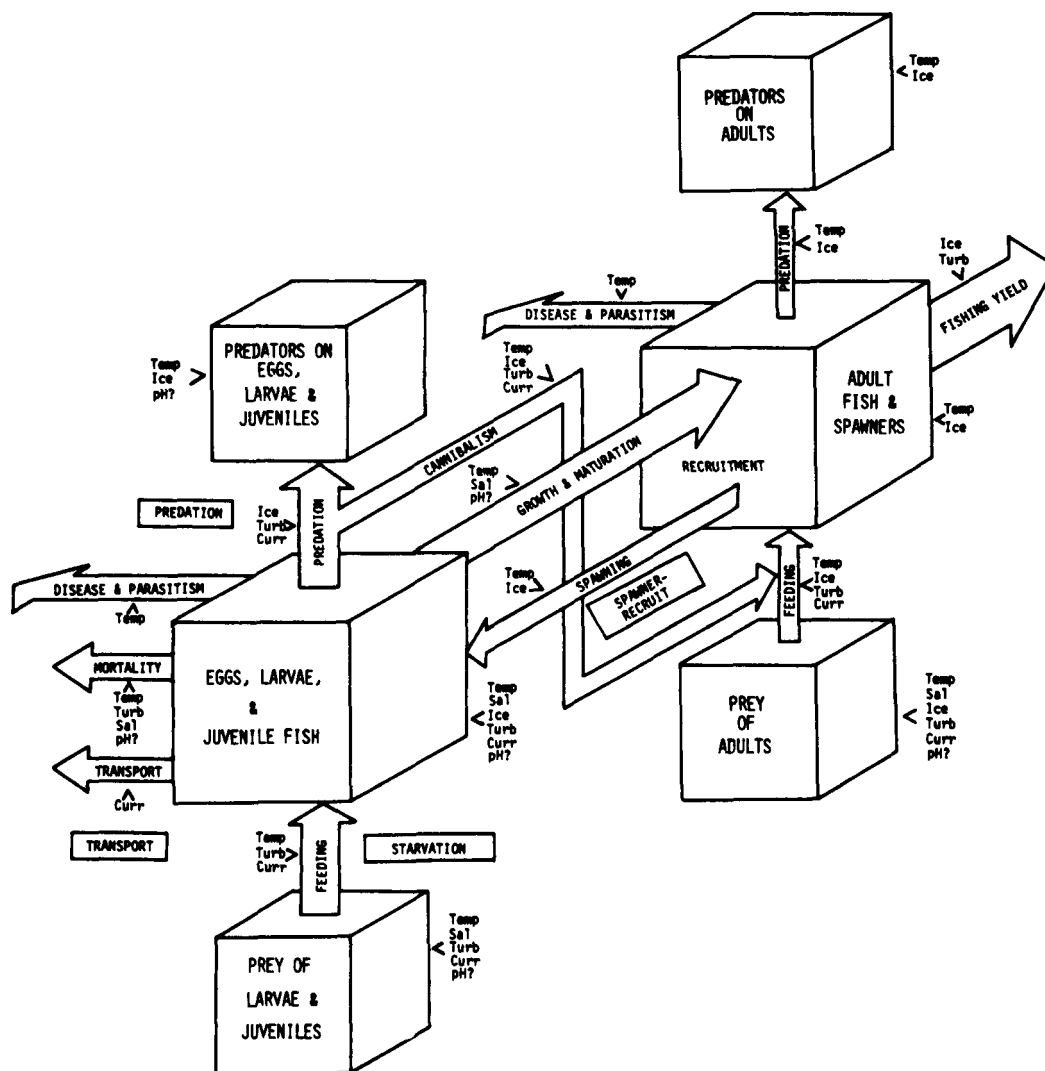


Figure 5.5. Major biotic processes affecting fish production and the abiotic factors that modify these processes. The four major hypotheses concerning control of fishery abundance are related to the major processes controlling production and mortality of early life history stages: reproductive output, starvation, predatory (including cannibalistic) losses, and transport losses. To represent an actual fishery environment several such interlocking diagrams would be needed to depict multiple species.

and subsequently from the atmosphere. There is considerable disagreement concerning the possible effect of increased CO_2 on this process. Stumm and Morgan (1981) argue that the oceans are currently oversaturated with CaCO_3 relative to the principal precipitation products calcite and aragonite and will remain saturated with a doubling of atmospheric CO_2 . Therefore, there is no reason to expect an effect on precipitation. Brewer (1983) indicates that increased dissolution of CaCO_3 shells not only appears inevitable but probably has already begun. Increased understanding of this problem is essential both for predicting the effect on biota and for assessing the role of marine biota on the global carbon cycle.

Major changes in water chemistry will be reduced pH and changes in the speciation of essential nutrients and toxic trace metals. Changes in pH are not expected to have major effects on most marine organisms (Knutzen 1981), but there has been too little experimental research to ensure confidence in this projection. Trace metals will certainly become more available to marine organisms. In nearshore regions, where the concentration of metals is higher, concentrations of some metals may become high enough to be toxic to sensitive organisms. However, in the open ocean the increased availability of essential minor nutrients actually may be stimulatory for some phytoplankton species.

5.2.2.2 *Effects of Temperature*

Changes in temperature can produce fish responses that range from changes in enzyme reaction rates to altered biogeographic distribution patterns. Fish and their prey are poikilothermal (cold-blooded) organisms whose body temperature and resultant metabolic rates are determined by environmental temperatures. As temperature increases, the metabolism of these organisms increases immediately, typically by a factor of 2–3 for an increase of 10°C (Fry 1971; Eppeley 1972; Clarke 1983). Opposite effects would be expected in homeothermic (warm-blooded) organisms such as birds and mammals that prey on fish. Over a longer time period, organisms have some compensatory mechanisms that reduce the magnitude of metabolic fluctuations (Clarke 1983). Specific temperature effects will depend on an organism's adaptation to a specific environment. Because the increased metabolic rates apply to both anabolic and catabolic reactions, the net effect of temperature changes on organisms is not always apparent. Although marine organisms will typically grow and mature more quickly at higher temperatures, increased growth rates depend on adequate nutrition for both plants and animals; moreover, even with sufficient nutrients there may be increased natural mortality.

The biogeographic distribution of organisms is limited by temperature patterns (Laevastu and Hayes 1982; Shepherd et al. 1984). Each species or stock tolerates a temperature range with a preferred temperature interval in that range that optimizes survival and growth. As a result the geographic (especially latitudinal) distribution of a species primarily depends on temperature. For aquatic species, the depth at which they live also may be determined by temperature. The temperature range and optimum of a fish species may vary with the stage of the life cycle (see Table 5.2), and migrations may occur to maintain each stage within its tolerance range.

Regions of the ocean with permanent or seasonal ice cover are harsh environments that are generally inhabited by specialized organisms (Clarke 1983). Because convection below the ice cools the marine water column to near-freezing temperatures to great depths, most fish that can migrate move to deeper water in winter, and those organisms that cannot migrate may have significant growth retardation. The physical barrier of ice cover also prevents many birds and mammals from preying on fish in certain areas and during certain seasons. However, certain marine organisms, including obligate ice-dwelling predators such as polar bears and walruses have evolved strategies to exploit ice cover, and prey species in polar regions find refuge from predation in extremely cold waters. In addition, the stable surface layer that results from icemelt produces high rates of primary production and large planktonic food supplies for fish.

Warming of sea surface temperature will have the general effect of shifting species ranges and migration patterns poleward. The mechanism of this shifting will act through changes in abundance due to physiological effects on organisms at the present fringes of their distribution. The extent of these shifts will depend on the species and its habitat. Epipelagic (near-surface) species will experience the greatest temperature changes, but may also have the broadest temperature tolerances. The shifts also will depend on the rate and variability of warming and on the rate of possible genetic adaptation in the population. Reductions in ice cover, which may be the most noticeable temperature-related abiotic change, could increase the total area of the ocean that is habitable by commercial fish species.

The most significant biological effects associated with temperature are probably caused by changes in abundance and distribution of prey, competitors, pests, predators, and disease and parasitic organisms. A temperature increase will accelerate the metabolism and life cycles of all species; the extent of the acceleration will vary among species. Changes in temperature can cause changes in the timing of fish spawning and

Table 5.2
Characteristics of Case Study Species

Characteristic	Alaska Pollock	British Columbia Herring	Alaska Pink Shrimp	Bering Sea Yellowfin Sole
Life History				
Recruitment	Ages 2–3	Ages 3–4	Age 2?	Ages 4–7
Maturity	Ages 3–4	Ages 3–4	Alternation of sexes; Male at 2 1/2 to 3 1/2; female at 5 1/2; sterile at 6 1/2.	Ages 4–9
Life span	To 18 years	10+ years	To 7–8 years	To 15+
Habitat				
Range	North Pacific from Washington (47°N) to Chukchi Sea (70°N) to Korea (35°N).	North Pacific from northern Baja to Arctic Ocean to Korea; commercial California to central Alaska.	Circumpolar from Arctic Ocean (82°N) to Gulf of Maine (41°N) and Columbia River (46°N).	North Pacific from British Columbia (50°N) to Chukchi Sea (70°N) to Korea (35°N).
Stock structure	Possibly northern and southern stocks in Bering, one in Aleutians, eastern and western stocks in Gulf.	Distinct stocks spawned on each of many beaches.	Distinct stocks in each of many small bays.	Possible northern and southern stocks.
Adult	Semidemersal: schooling near bottom and mid-water, 40–500 m depth; outer continental shelf and upper slope, some inland and oceanic stocks.	Pelagic 5–40 m summer, 50–80 m winter; inner continental shelf.	Mud bottom, high organic content. 50–400 m depths on continental shelf and upper slope.	Demersal, continental shelf and upper slope to 400 m, especially in submarine valleys.
Spawning	Outer continental shelf and slope near bottom in spring (February to June).	Shallow near shore (0–20 m) on vegetation in spring (later to north).	Near shore late summer and early fall; eggs carried by female; released to hatch near bottom from March into summer.	Near 50 m isobath July to September; possible surfaceward migration.
Larval and juvenile	Pelagic 0–40 m over middle and outer continental shelf; semidemersal beginning age 2.	Inshore, in colder water.	Planktonic larvae; juveniles near hatch sites, shallower than adults.	Shallow water near shore until age 4.
Migrations	Deeper than 200 m offshore and southerly in winter, onshore and northerly in summer; diel vertical feeding migration.	Onshore to spawn, initiated by stratification or photoperiod; diel vertical feeding migration.	Little alongshore; onshore to spawn autumn; diel vertical feeding migration.	90–360 m and southerly winter; onshore and northerly to 50 m or less summer.

Table 5.2 (continued)

Characteristic	Alaska Pollock	British Columbia Herring	Alaska Pink Shrimp	Bering Sea Yellowfin Sole
Abundance	Bering stocks fished at capacity but healthy; Aleutian and Gulf underfished and at historic highs.	All stocks overfished and depleted.	All stocks overfished and depleted.	Formerly overfished and depleted, now has recovered to historic abundance.
Trophic Status				
Prey	Juveniles: zooplankton (copepods and euphausiids). Adults: zooplankton and small fish (especially pollock).	Juveniles: zooplankton Adults: zooplankton	Juveniles: zooplankton Adults: zooplankton, benthos, detritus?	Bivalves, polychaetes, crustaceans, echinoderms do not feed in winter.
Predators	Fur seals, sea lions, murre, kittiwakes, cod, pollock, salmon.	Adults and juveniles: dogfish, whales, pollock, salmon. Eggs and larvae: seabirds and jellyfish.	Fish, especially cod, pollock and flatfishes; seals.	Halibut; others?
Competitors	Herring, cod, rockfish, salmon, murre, shearwaters, kittiwakes.	Adults: capelin, juvenile sockeye salmon.	Fish, euphausiids?	Plaice, rock sole?
Temperature Relations	Adults: 1 to 7.5°C. Spawning: 1 to 3°C. Juveniles: -1.5 to 11°C. Spring migration limited by cold bottom water.	Adults: above 40°C. Spawning: 3 to 12°C. Juveniles: Cooler than adults.	Adults: -2 to 11.5°C. Spawning females and larvae may have narrower tolerances.	Eggs: 6.4 to 11.4°C. Adults: 3.5 to 6°C. Winter: -0.5 to 2°C. Spring: 0 to 11°C. Summer (concentrate at lower end of range) more concentrated in warm years; spring migration limited by cold bottom water.
Probable Factors Controlling Year-Class Strength	Bering Sea: cannibalism and predation? Gulf of Alaska: advective loss?	Offshore advection?	Predation?	Predation?

Note: (?) = Uncertainty in our present understanding.

migration in addition to direct effects on fish growth rates. The availability of food may also change if temperature alters the plankton growth cycle.

Numerous investigations have correlated fish catches with surface water temperature (Cushing and Dickson 1976; Sutcliffe et al. 1977), although the mechanisms by which temperature may act have generally not been specified. Cushing (1982) compared historical data on fishery yield with climate trends. During the first half of this century, mean air temperature in the Northern Hemisphere rose about 0.5°C, and there were incidental sightings of many fish species far north of their accustomed ranges. Also, there was a clear northward shift of the geographic range of two major fishery species: cod (*Gadus morpha*) and herring (*Clupea harengus harengus*) in the northeast Atlantic. Cod distributions expanded from Greenland to Iceland. The shift reversed about 1950 and produced increased populations of gadoids (cod-like fishes) in the North Sea that were correlated significantly with decreasing sea surface temperature (Cushing 1984). The mean air and sea surface temperature change associated with these shifts was less than 1°C over a period of about two decades. It may be inferred that a temperature threshold for fishery effects could be less than 1°C, although it is not clear that temperature alone was responsible for the observed changes.

Temperature is often regarded as an index for a suite of environmental changes that include atmospheric pressure, winds, currents, vertical mixing, and changes in plankton abundance and species composition. Cushing (1982, 1984) argued that changes in cod abundance in the North Sea were most significantly influenced by the seasonal timing and magnitude of plankton blooms and only secondarily influenced by March sea surface temperature. The 1982–1983 El Niño in the Pacific demonstrates that ocean basin-wide spatial scales must be considered in the understanding of many important environmental fluctuations.

Analysis of climate trends is limited because environmental variability over time scales of a year or less can be more important than the mean decadal changes. For example, long-term trends in temperature have not been linked to declines and shifts in fishery yield resulting from El Niños. However, the extreme magnitude and rapidity of environmental fluctuations in this region have produced short-term biological effects that are at least as great as those observed in the North Atlantic. During the 1982–1983 El Niño, biological effects associated with changes in mean sea surface temperatures of 2°C for a period of 6 months or less were among the most dramatic ever observed in the northeastern Pacific (McGowan 1984; Reed 1985). Similarly, CO₂-induced climate changes may

alter environmental variability at the time scale of weather and produce effects that are more important than the effects of gradual, long-term climatic trends.

5.2.2.3 Effects of Turbulence

The biotic effects of turbulence on fish include metabolic losses incurred because animals need to expend more energy to maintain their positions in turbulent waters. In addition, there is evidence that strong turbulence can directly increase the mortality of some organisms during sensitive life stages, especially by destroying the eggs. The dominant biotic effects of turbulence, however, are probably mediated by changes in food supplies.

The balance between turbulence and vertical stability has a major effect on primary production. Strong stability favors a high photosynthetic rate by phytoplankton because it retains these floating plants near the surface where there is sufficient light, rather than allowing them to be mixed to greater depths where photosynthesis is limited by lack of light. These plants also require dissolved mineral nutrients, however, and the reduced mixing associated with strong stability allows nutrient depletion as plants utilize the available nutrients. The principal means of replenishing these nutrients is vertical exchange with deeper water. Thus, the most favorable conditions for primary production are those of constant moderate stability or of spatial and temporal variability in stability. These conditions optimize the conflicting needs of plants for both sunlight and nutrients, for stability and mixing.

The general global increase in surface water stability associated with climate warming is expected to decrease primary productivity in the already stable waters of the tropics and subtropics and increase it in the less stable regimes of mid to high latitudes. Local exceptions would be expected in areas influenced by upwelling or freshwater sources, especially in regions of increased winds. These changes would appear to be generally beneficial for commercial fisheries, most of which are at higher latitudes or in upwelling areas.

Vertical stability and reduced vertical mixing produce spatial heterogeneity of organisms, or "patchiness." Patches are hypothesized to provide, under different circumstances, both a refuge from predation for some prey species (Francis and Bailey 1983), and concentrations of food for consumers (Lasker 1975). Turbulence disrupts these aggregations, increasing predatory losses of some species and dispersing and reducing the food supply of others. No studies have attempted to evaluate the net effects on a single species of simultaneous changes in food supplies and predation pressures caused by turbulence.

The balance between turbulence and stability also is believed to affect the species composition of phytoplankton, which in turn can influence the diets of selective feeders at higher trophic levels (Greve and Parsons 1977). Recent research suggests that in nutrient-deficient, stratified surface waters and in downwelled or extremely turbulent waters, the phytoplankton is dominated by smaller, generally less productive species that are motile and can regulate their depth distribution to optimize their exposure to light and nutrients. In areas of upwelling or moderate turbulence the phytoplankton is dominated by a larger, nonmotile but more productive group, the diatoms. Diatoms are believed to provide greater fishery yields, both because they are more productive and because they support food webs with fewer trophic levels and a higher ecological efficiency (Ryther 1969). Furthermore, the sinking of diatoms to the bottom is believed to provide a greater food supply for bottom-dwelling fishes and their prey (Walsh 1983).

5.2.2.4 Effects of Currents

Currents tend to transport organisms in the same direction as flow. Larger, swimming animals may resist this transport or avoid it by migrating to deeper or more sheltered waters. Smaller, weaker organisms such as larval fish and other plankton are more susceptible to transport. In some instances (e.g., dispersal of planktonic larvae of some sedentary benthic species) this transport may be considered advantageous for colonizing new habitats. Other organisms may have adapted their life cycles and migratory patterns to avoid currents that could remove them from favorable environments. In such cases other horizontal motions such as eddies or internal waves (Mysak et al. 1982) may become important.

Additional effects of currents on fish are mediated through effects on food supplies. Off the California coast prey abundance has been linked to the strength of horizontal currents (Chelton et al. 1982). However, the best-known effects of currents on prey are those of vertical currents. The upwelling and downwelling areas of greatest biological significance occur along coastlines. When wind-driven surface currents parallel a coastline, water is transported either onshore (coastal downwelling) or offshore (coastal upwelling). Coastal upwelling is highly favorable for primary production because it both retains phytoplankton within the euphotic zone and provides nutrients for sustained growth; that is, it combines the beneficial aspects of both turbulence and stability. The most productive regions of the ocean are the eastern boundary current upwelling areas such as the coast of Peru (Ryther 1969). Upwelling also enhances the productivity in open ocean

waters along the Equator and surrounding Antarctica. Paradoxically, despite increasing food supplies, strong coastal upwelling sometimes may decrease survival of larval fish by transporting them seaward toward a less favorable offshore habitat (e.g., Bailey 1981).

Changes in current strength, direction, timing, and location all could significantly alter the effects of currents on fish yield. It cannot be assumed that upwelling areas will shift poleward along with wind patterns unless the coastline is properly oriented. Fish generally avoid strong currents, so that weakening of currents may be beneficial. Increased strength of coastal currents at high latitudes due to increased freshwater addition could be quite significant for major fisheries.

5.2.3 Hypotheses of Dominant Mechanisms Controlling Fishery Abundance

To understand the causes of fluctuations in fishery yield, it is necessary to study more than simple changes in total population numbers or biomass. It is also necessary to examine the population age structure, which varies because of fluctuations in abundance of fish cohorts produced in individual years. The abundance of an annual cohort is termed "year-class strength." As recently as 25 years ago (Beverton and Holt 1957) it was generally believed that year-class strength depended mainly on the abundance of the adult spawning population. However, present theories are outgrowths of the classic study of Hjort (1914), who first suggested that year-class strength could be controlled by survivorship at very early life stages, rather than by growth and survival patterns after maturity. Fish mortality rates are typically very high and variable during the egg and larval stages, but drop significantly and become relatively more stable during the juvenile phase. For most natural populations reproductive output appears to exceed that required to maintain the population, and differences in environmental (physical and biological) factors affecting mortality during early life history stages probably determine variations in reproductive success.

The strength of a year-class is established during the first few months of life, but its effects persist throughout the life span of the cohort, which may range from 3 to 20 years in different species. Single, strong year-classes, interspersed among weaker year-classes, can dominate the fishery catch for several years (Anderson 1981). However, substantial and prolonged increases or decreases in the exploitable biomass of fisheries are the product of a series of successive strong or weak year-classes. These effects may be propagated further if they significantly affect the reproductive capacity of the stock.

Unfortunately, there is a lag between the time when environmental stimuli act on the early life stages of fish and the time when these effects are observable. There usually are no reliable population estimates for fish before they reach the age of "recruitment" to the fishery (the age when fish are large enough to be caught by commercial gear). Recruitment age is generally close to the age of sexual maturity and may range from 9 months for small, short-lived fish such as anchovy to 9 years for large, long-lived fish such as halibut. Surveying abundance of prerecruits (larval and juvenile stages) is time consuming, expensive, and not necessarily reliable.

Because the determinants of year-class strength occur before recruitment to the fishery, during periods of the life cycle that are not easily monitored, the factors determining year-class strength have not yet been observed directly. The exact ages and the particular environmental conditions that are important are not yet known and may vary spatially, temporally, and among species. Moreover, slight differences in mortality rates or developmental times that are too small to be measured easily may produce large differences in year-class strength (Houde 1982). Such slight changes may result from subtle rather than major environmental changes or from interactions among different factors. Thus, the most important controlling processes may be particularly difficult to detect.

Fishery researchers have approached this problem by attempting to correlate fishery and environmental data sets. Although the statistical problems associated with this approach have been enumerated by several investigators (Bell and Pruter 1958; Austin and Ingham 1978; McCaughran 1983), it continues to be popular. Correlation coefficients identify events that appear coincidentally and can suggest possible interactions between environmental factors and fishery responses. However, a high correlation does not identify the mechanism relating the two factors. Because of the statistical limitations it is important that the correlations be considered as generating hypotheses rather than as providing explanations (Shepherd et al. 1984). The hypotheses generated by his approach should correspond to those that can be supported by theoretical mechanisms and should be tested where possible by controlled experiments.

There are few proven examples of environmental mechanisms that control fishery year-class strength. However, from all the abiotic and biotic processes described above, several working hypotheses have evolved concerning the probable major mechanisms (Wooster 1983; Hunter 1983). Efforts are now underway to determine which of these proposed mechanisms may be most important for individual fish stocks. The relative importance of individual mechanisms probably

will vary at different times and locations, and multiple rather than single mechanisms probably will determine year-class abundances.

The "spawner/recruit" hypothesis that reproductive success is limited by the number of spawning adults is most relevant to badly overfished stocks. Currently, many major stocks are overfished, so that the abundance of the spawning population clearly is an important consideration. However, certain depleted stocks recently have made surprisingly rapid recoveries (Kondo 1980; Gulland 1983). These recoveries suggest that our knowledge of mechanisms controlling survival still is incomplete and that even low egg production may be sufficient under proper environmental conditions.

There are several mechanisms by which "starvation" may regulate year-class abundance. The time of larval "first-feeding" after hatching and yolk sac absorption is considered a particularly sensitive period (Hunter 1981). If feeding were limited simply by total prey abundance, then survival of fish larvae would decrease as their numbers increased and would be "density dependent" (Peterman 1978). Theoretically, at high enough larval abundance, food supplies would become inadequate, but currently there is little evidence for such density dependence in nature (Cushing 1983). Methods are being developed to estimate the incidence of starvation in the field (e.g., O'Connell 1981; Theilacker 1978).

Two other "density-independent" starvation mechanisms depend more on spatial and temporal distributions of prey than on their abundance and could operate regardless of larval abundance. The "match/mismatch" hypothesis developed by Cushing (1975) for the North Sea suggests that starvation could result if fish spawning is poorly synchronized with seasonal abundance patterns of prey. Spawning time is mostly genetically controlled, whereas plankton growth is controlled mostly by abiotic factors that have considerable interannual variability.

The "nursery layer stability" hypothesis was derived for California anchovies by Lasker (1975). It postulates an interaction between water column stability and food concentration. If vertical stability permits prey organisms to be spatially aggregated, a low mean prey density is sufficient for larval survival because the fish larvae can feed efficiently. However, the same mean prey abundance could be inadequate if prey aggregations are disrupted by turbulence. The match/mismatch and stability mechanisms are not mutually exclusive.

"Predation" also may be extremely important to larval fish mortality, but its magnitude is difficult to quantify in the field. All life stages of fish may be susceptible to predation by other fish, birds, or mammals and some invertebrate species may produce

significant mortality by predation on larval fish (Bailey 1984; Moeller 1984). Predation effects may be either density dependent or independent.

The "transport" hypothesis also postulates a larval nursery habitat—one in the horizontal dimension. Removal of larvae from this nursery by currents decreases the probability for survival (Parrish et al. 1981). Bailey (1981), for example, has demonstrated that the survival rate of Pacific hake (*Merluccius productus*) larvae was reduced when they were transported far offshore from their nursery habitat close to the California coast. Mortality may be caused by starvation, predation, or other causes. Transport acts regardless of larval abundance and therefore is a density-independent mechanism.

The effects of increased CO₂ on a particular fishery will depend both on the unique characteristics of the abiotic and biotic environment and on which of these hypothetical mechanisms are important. A case study approach was used to evaluate individual fisheries in the northeastern Pacific Ocean.

5.3 CASE STUDY ANALYSIS

Each fish species will respond differently to climate change. Therefore, it is not possible to provide detailed predictions of the global fishery response to potential climate change. Individual case study fisheries were selected to better define our current understanding of the relationship between climate and marine fisheries production and to identify improvements in data and research methodology needed to eventually determine the consequences of CO₂-induced climate change on fisheries.

5.3.1 Selection of Case Study Fisheries

5.3.1.1 Geographic Area

The region selected for the case studies is the coastal northeastern Pacific from approximately 50° to 65°N and 120° to 180°W (Figure 5.6). This region contains three subareas: the eastern Bering Sea; the Gulf of Alaska; and the coast of British Columbia, with several relatively well-studied, economically important fisheries. The coastal waters of Alaska, Oregon, and Washington produce approximately 50% of the weight and 40% of the economic value of fish catch in U.S. territorial waters. Important commercial fisheries are also located at comparable latitudes in the North Atlantic. In addition to being highly productive, the North Pacific and North Atlantic fisheries are the most intensively studied marine fisheries in the world and offer the

greatest opportunity for observing and interpreting historical trends.

Subpolar latitudes were chosen for this because significant climate change due to increased atmospheric CO₂ is predicted for these latitudes, and because they should be particularly sensitive to such changes. The greatest increases in temperature and precipitation are predicted for high latitudes, especially in winter (NRC 1983). The study area experiences enormous seasonal and interannual fluctuations in temperature and other environmental conditions, including extensive winter ice cover in the Bering Sea. Moderation of winter conditions, especially the reduction of seasonal ice extent, could be among the most sensitive indicators of climate change.

The study area also may provide the most sensitive indicators of effects of climate change on marine organisms, such as poleward shifts in geographic ranges and in biological transition zones associated with strong environmental gradients (Cushing 1982). The northernmost ranges of several commercial fish species are limited by winter conditions in the Bering Sea and could expand significantly as a result of warming. Because subpolar fishes are exposed to a greater seasonal and interannual range of environmental parameters, the limits of their physiological tolerance may be challenged more frequently than those of species from more stable low-latitude environments. Consequently, relatively slight changes in environmental factors may have a greater impact on subpolar species than on species from more temperate habitats.

At a given latitude, the most sensitive marine environments are continental shelf waters because they have the greatest exposure to the atmosphere and to the hydrologic cycle. They also yield 99% of global marine fish catch (Ryther 1969). Shallow coastal waters generally are most susceptible to climatically driven fluctuations in temperature and salinity because they are partially segregated from the more stable reservoir of the deep ocean. Changes in turbulence and currents will have the greatest effects in shallow continental shelf waters because their effects can be propagated through the entire water column.

The Bering Sea and the Gulf of Alaska are at similar latitudes but have very different bathymetric, current, and climate conditions and should respond differently to climate change. The eastern Bering Sea is characterized by sluggish (1–10 cm s⁻¹) currents, extensive winter ice cover, and an extremely wide (500 km) continental shelf. The shelf region is divided into three domains: a turbulent coastal domain shoreward of the 50 m isobath; a strongly stratified middle shelf domain between the 50 and 100 m isobaths that has extremely cold bottom water generated by overlying winter ice cover; and an outer

shelf domain that extends to the shelf break at about the 180 m isobath. The bottom is relatively smooth and has few bathymetric irregularities.

The Gulf of Alaska and British Columbia continental shelves are narrower with little ice cover or cold bottom temperatures and possess strong ($50\text{--}100\text{ cm s}^{-1}$) coastal currents. Large volumes of water enter the region from the open Pacific via the Subarctic Current, which is diverted northward to form the warm Alaska Current and the Alaska Stream. These currents transport large quantities of heat that moderate temperatures in the region. Portions of the shelf in this region are wider and have shallow offshore banks and islands (such as Kodiak Island, the Queen Charlotte Islands, and Vancouver Island), with deeper sheltered straits and canyons (such as Shelikof Strait and Georgia Strait) behind them. Both the Pacific and Bering regions have very steep continental slopes separating the shelf from deeper oceanic waters and are fed by major coastal

freshwater sources. Freshwater input dominates the hydrography of the Pacific shelf but affects only the coastal domain of the Bering region. Tidal currents are strong (50 cm s^{-1}) on all the shelves.

5.3.1.2 Case Study Species

The species we have chosen to study are Alaska pollock (*Theragra chalcogramma*), a semi-demersal (near-bottom) fish that currently supports the world's largest fishery; Pacific herring (*Clupea harengus pallasi*), a pelagic (near-surface) species that is known to have large fluctuations in population abundance; yellowfin sole (*Limanda aspera*), the second most abundant commercial species and most abundant demersal (bottom) fish in the Bering Sea; and pink shrimp (*Pandalus borealis*), a demersal crustacean species with a circumpolar distribution. The biological criteria for selecting these species is detailed in Strickland et al. (1985). Although no species is likely to have all the desirable characteristics

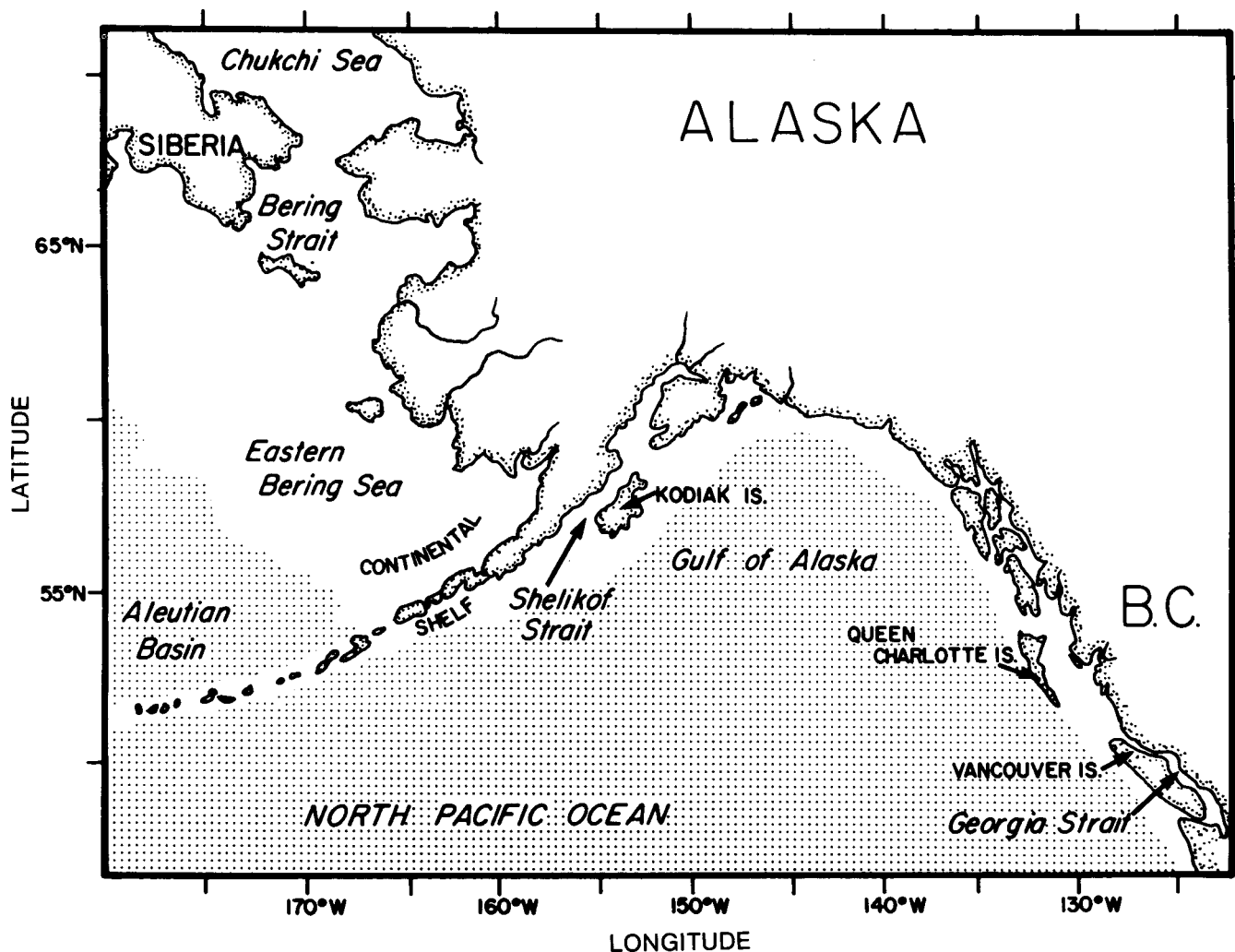


Figure 5.6. Base map of case study region from British Columbia (49°N) through the eastern Bering Sea (67°N).

for evaluating responses to environmental fluctuations, these economically important species represent a range of habitats and life history strategies (Table 5.2), and should exhibit diverse responses to potential climate change. The clupeid (e.g., herring, anchovy, sardines) and gadid (e.g., pollock, cod) families are the two most important commercial fish families in the world in terms of tonnage and human consumption, respectively.

A significant natural variability in recruitment is essential for detecting responses to climate change (Wooster et al. 1983), and several factors may contribute to the variability or the stability of recruitment in fish populations (Austin and Ingham 1978). Stable population density may be favored by greater fecundity. Cushing (1980) argued that North Sea cod populations are more stable than herring because of greater fecundity. Francis and Bailey (1983) also noted that Alaska pollock has lower variability in recruitment and smaller population fluctuations than other northeastern Pacific species with lower fecundity. Interannual fluctuations in abundance also tend to be smaller in species that have longer life spans, such as pollock and sole, than in short-lived species such as herring and shrimp. The portion of the life span spent in the plankton, or feeding on plankton, also could influence variability. Surface waters and planktonic organisms undergo much greater variation than deep waters and the fish and benthic organisms that inhabit them. By this criterion shrimp and sole should have more constant recruitment than pollock, and herring recruitment should be the most variable.

Pollock may be the best indicator of climate change because of conflicting needs for recruitment stability and exposure to variable surface conditions. However, the high incidence of cannibalism in Bering Sea pollock confounds our interpretation of its climate response. Austin and Ingham (1978) considered cannibalism to impose an additional source of biotic variability that makes it more difficult to identify and interpret climate effects. Alternatively one could argue that cannibalism is a homeostatic mechanism that decreases variability (Ursin 1982).

Heavily fished or overfished populations are more susceptible to environmental fluctuations. Population "crashes" in numerous species have been blamed on environmental perturbations that further depleted already overfished stocks (Lasker 1981). In extreme cases fishing can completely overwhelm environmental influences. For example, despite mild winters, which were expected to enhance the Bohuslan herring stocks during the 1950s and 1970s, the stocks did not recover because they lacked adequate reproductive potential (Sjoblom 1978). Similar scenarios have been observed in the Peruvian anchovy and California and Japanese

sardines (Cushing 1983). To some degree, all of the case study species have been overfished recently. However, a case study species must have a substantial fishery, or it will be difficult to obtain necessary data, such as age structure, for detailed analysis (Wooster et al. 1983).

Species that have several different "well-defined" substocks (such as salmon, in which each spawning stream supports a genetically distinct subpopulation) are preferable analytically to large, single-stock populations because the different substocks can each be treated as separate experimental populations (Wooster et al. 1983). The stock structures of pollock and sole are uncertain but there are probably few distinct stocks in the study area. In contrast, distinct stocks of herring exist at each spawning beach, and multiple shrimp stocks are found in discrete demersal habitats.

5.3.2 Projected Environmental Effects

The specific impacts of climate change will differ in localized habitats because of factors such as latitude, proximity of land masses and orientation of shoreline, bottom topography, and tidal currents. Specific responses in the northeast Pacific and eastern Bering Sea may differ significantly, and may even be opposite, over relatively small distances (such as the 100-km width of the Alaska Peninsula), because of differences in abiotic factors such as atmospheric pressure, wind, ice cover, and currents.

5.3.2.1 Temperature, Salinity, and Ice Cover

Climate warming will generally warm surface waters, with a tendency toward greater relative warming at higher latitudes and during the winter (NRC 1983). This increment will vary regionally depending on local atmospheric and oceanographic properties, including cloudiness, winds, precipitation, ice cover, vertical mixing of the surface layer, and currents. Warming effects should be less evident in the temperate northeast Pacific, where currents transport significant quantities of heat from the south than in the subpolar eastern Bering Sea where heat transfer is primarily across the air-sea interface.

The northeast Pacific and eastern Bering Sea are regions of relatively low salinity due to large inputs of precipitation and runoff. Mean surface salinities would decrease substantially, according to scenarios of climatic warming that project increases in net precipitation and runoff at higher latitudes (NRC 1983). Seasonal salinity patterns may be affected if there are shifts in the seasonal distribution of precipitation, especially if precipitation falls as rain rather than as snow and if there is runoff earlier in the season. The largest changes

in salinity might be expected near river mouths and in the nearshore regions. Eastern Bering Sea shelf waters are strongly influenced by the copious runoff from the Yukon and Kuskokwim Rivers in the very nearshore domain, but not on the middle and outer shelf domains where the case study fisheries are centered. These domains may be affected by input of water from the Kenai Current of the Gulf of Alaska, however. The Kenai Current is a fast, narrow stream that extends close to shore along the southcentral Alaskan coast and is strongly driven by winds and coastal runoff from the eastern Gulf. It is expected that hydrologic changes would have major effects on water transport in the Gulf, and possibly on the hydrography of the southeastern Bering Sea.

Changes in ice cover over the eastern Bering Sea shelf affect and are affected by changes in water temperature and salinity. Ice is neither a source nor a sink for fresh water in the eastern Bering Sea on an areal or annual average; it freezes and remelts in roughly the same locations. However, icemelt significantly lowers the surface salinity over the middle and outer domains of the continental shelf and increases the surface vertical stability. Under present conditions this stable surface layer insulates the deeper water of the middle shelf domain from summer warming, such that bottom temperatures are colder in years when surface temperatures are warmer.

The difference in response to climate change between the Gulf of Alaska and the eastern Bering Sea will be magnified by effects on Bering Sea ice cover. Under present conditions ice covers nearly the entire continental shelf of the eastern Bering Sea in cold years but covers only the very northern shelf in warm years (Figure 5.7). Climate warming seems very likely to greatly reduce seasonal ice cover in this region or eliminate it all together. Some studies (NRC 1983) predict that the Arctic Ocean may become ice free in summer. Paradoxically, the weakening of surface water vertical stability caused in part by a reduction in the buoyant icemelt layer may partially offset the anticipated surface temperature increase in this area. Correspondingly, reduced surface stratification could cause disproportionate increases in bottom water temperatures on the eastern Bering Sea shelf.

5.3.2.2 Turbulence and Currents

These forms of water motion are both driven and modified by atmospheric forcing and by pressure and density gradients arising from temperature and salinity distributions and runoff. In some instances climate change may alter these properties in ways that counteract each other, creating some uncertainty about the net direction and magnitude of climate impacts.

Uncertainty also arises from shifts in regional weather patterns that create local effects opposite to the general trend of climate change.

Under present conditions most northeastern Pacific waters are strongly turbulent and weakly stratified. Similar conditions exist in the coastal domain of the eastern Bering Sea, but more stable conditions associated with icemelt are observed on the middle and outer shelf domains. The projected increase in sea surface temperature and decrease in surface salinity in the study area will tend to increase vertical density gradients, decrease depth of vertical mixing and of the pycnocline, reduce turbulent exchange between surface and underlying water layers, and extend the seasonal duration of stratification.

Regional changes may be counteracted in local areas by several factors. For example, a global increase in wind velocities caused by heating could increase turbulent mixing and decrease stability. Furthermore, the prevailing North Pacific storm track, which overlies the Gulf of Alaska in winter and the western Aleutians in summer, could be displaced northward (Figure 5.8). Such a shift would cause increases in storminess and surface turbulence in the southeastern Bering Sea and

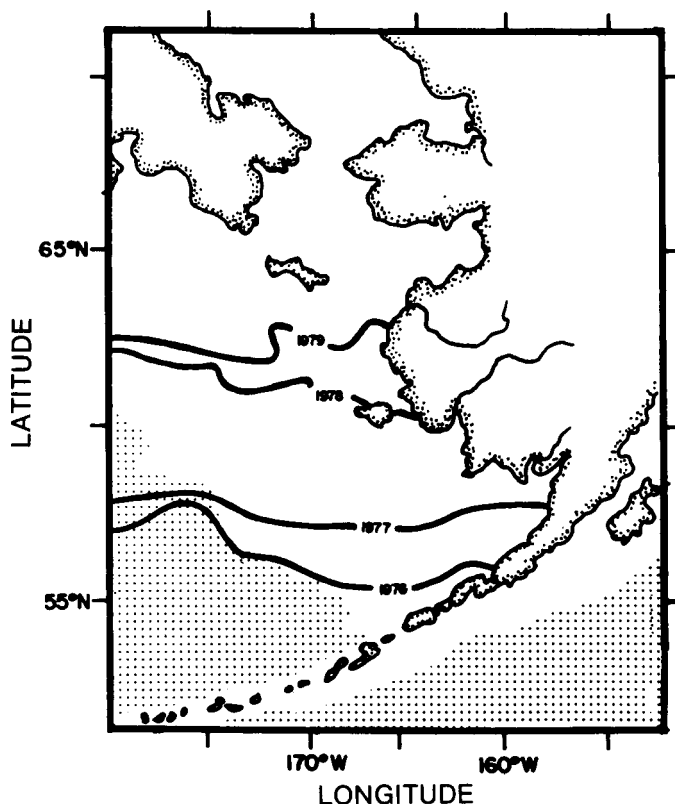


Figure 5.7. Variability of annual maximum (March–April) ice extent in the eastern Bering Sea during the late 1970s; (Ingraham 1981) represents the extremes of recent interannual differences during the coldest year (1976) and the warmest year (1979).

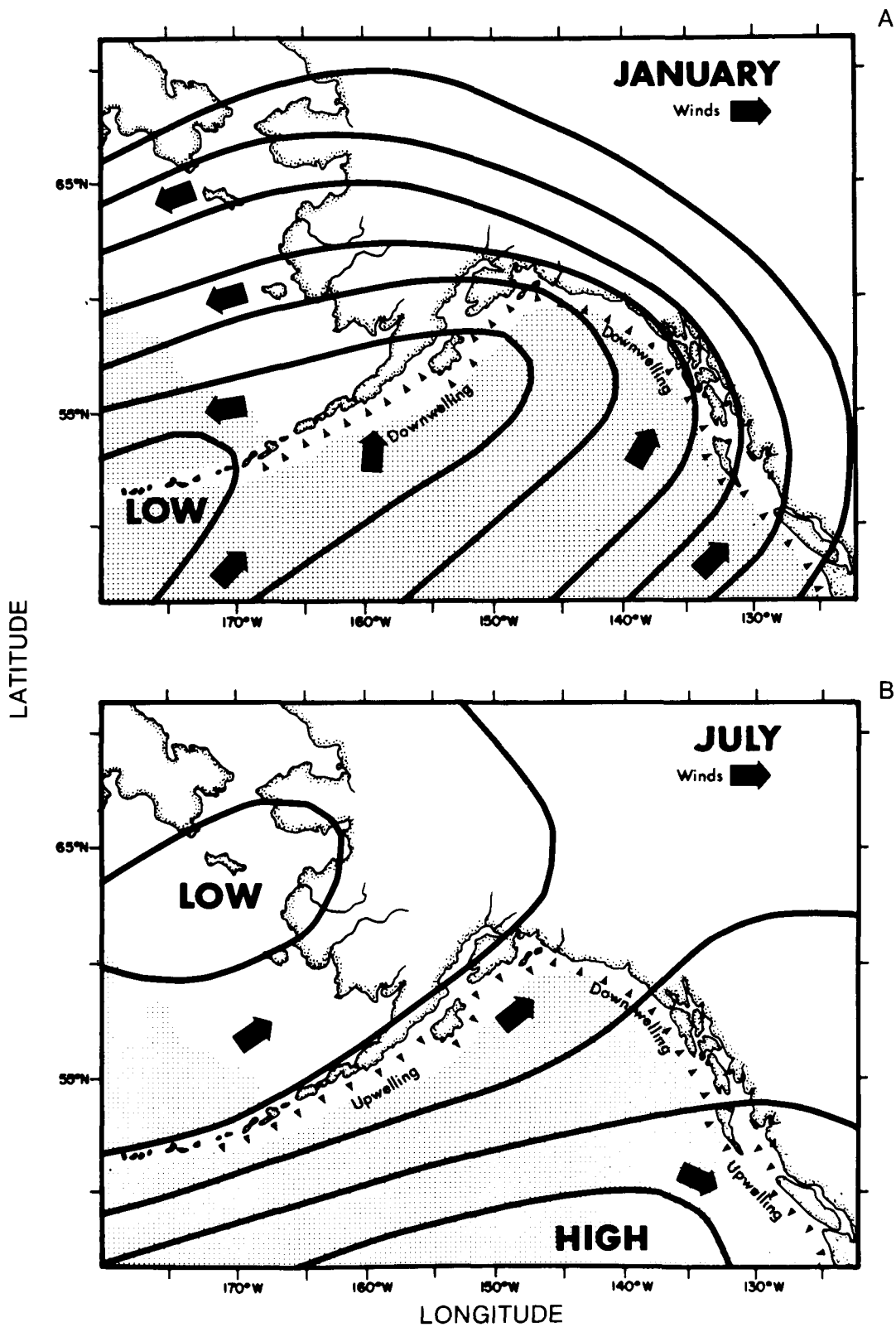


Figure 5.8. Present winter and summer mean distributions of atmospheric pressure and wind direction over the North Pacific region (after Favorite et al. 1977), and distributions of coastal upwelling and downwelling (after Ingraham et al. 1976; Parrish et al. 1981). Summer mean condition is used as a guideline for possible effects of future climatic warming.

decreases in the Gulf of Alaska. The removal of ice cover in the Bering Sea would enhance this effect in that area.

Decrease in wind velocities that should accompany warming would cause a general decrease in current strengths in the study area. However, the potential northward shift of the north Pacific storm track could produce increased winds and net southwesterly winds in the southeastern Bering Sea shelf domain—an area that now experiences no net wind direction. A lack of ice cover in the eastern Bering Sea in winter would permit increased wind forcing of the water column. Such a shift could induce significant horizontal advection where there now are very weak currents (Figure 5.9).

Increases in horizontal advection in the study area could be reinforced by stronger horizontal density gradients and entrainment associated with increased freshwater input. Intensification of currents could occur in the coastal domain of the eastern Bering Sea, which receives an enormous volume of runoff but has not been shown to have a strong coastal current. The greatest effects would occur where density-driven currents are strongest: the Kenai Current of the Gulf of Alaska and, to a lesser extent, along the coasts of southeast Alaska and British Columbia.

However, the advective effects of changes in winds and freshwater input appear to interfere with each other in the northeastern Pacific. Under present conditions cyclonic (counterclockwise) flow is maintained in the Gulf of Alaska by cyclonic winter wind stress associated with the Aleutian low-pressure center and by the constraining influence of the shoreline. This current system may be reversed or substantially weakened by a net increase in southwesterly wind stress associated with a northward shift of the Aleutian low (Figure 5.9). Such a shift currently occurs in summer for periods that are too brief to significantly affect overall mass transport. This decrease in circulation would counteract coastal intensification of currents caused by increased runoff.

A shift in prevailing wind patterns would also change relative rates of coastal upwelling and downwelling and the associated offshore and onshore transport. Under present conditions, downwelling caused by the combined effects of wind and runoff is inferred to occur along the entire Gulf of Alaska and the coast of British Columbia in winter and along the eastern Gulf coast all year. In response to a northward shift of atmospheric pressure patterns, the relative frequency, magnitude, and seasonal and areal extent of coastal upwelling and offshore transport might increase all along the coast of the northeast Pacific from the Aleutians through British Columbia (Figure 5.8). This effect would partially offset the tendency of freshwater input to cause increased onshore transport and coastal downwelling

in this region. Relative increases in coastal upwelling generated by this wind pattern also would reduce sea surface temperatures and increase surface salinities near shore, in opposition to the general trends.

5.3.2.3 *Lower Trophic Levels*

Under present conditions, spatial patterns of primary productivity in the study area appear to be controlled principally by vertical stability. Most coastal Gulf of Alaska and inner shelf Bering Sea areas appear to be more turbulent than is optimal for phytoplankton growth. Productivity in the eastern Gulf of Alaska is further diminished by coastal downwelling, whereas middle and outer Bering Sea shelf waters are more productive because of greater spring and summer vertical stability. Icemelt areas are more stable than is optimal, and high spring productivity is reduced in summer because of surface nutrient exhaustion. Thus the projected general decrease in turbulence, with locally increased turbulence over the deeper regions of the eastern Bering Sea shelf, may optimize surface stability properties and enhance primary production in all areas.

The only exceptions to this generalization are small areas in the Gulf of Alaska that already are strongly stratified in summer (weakly mixed nearshore areas, especially those influenced by runoff, such as Kachemak Bay, Auke Bay, and Prince William Sound), which will experience decreased summer productivity but an extended season. If much of the Gulf of Alaska and British Columbia also experience an increased frequency and magnitude of coastal upwelling, primary productivity will be further enhanced. In the middle and shelf domains of the eastern Bering Sea, elimination of icemelt, which brings strong stability early in the spring, would reduce productivity in the early season, but annual production should not decline because summer productivity will be enhanced by increased mixing and nutrient supply.

The taxonomic composition of the phytoplankton also may change. Except for species closely associated with sea ice, northward shift of phytoplankton species due to warming alone appears unlikely because a similar species composition occurs throughout the study area. However, species composition is affected by turbulence and currents. Diatoms are associated with upwelling and near-optimal stability conditions; strong turbulence and strong stability favor motile flagellates. There is some uncertainty about present species compositions in the study area because flagellates are difficult to observe or preserve and few data are available to describe their occurrence and ecology. The projections discussed above, however, indicate environmental changes that clearly are more favorable for diatoms. Increased

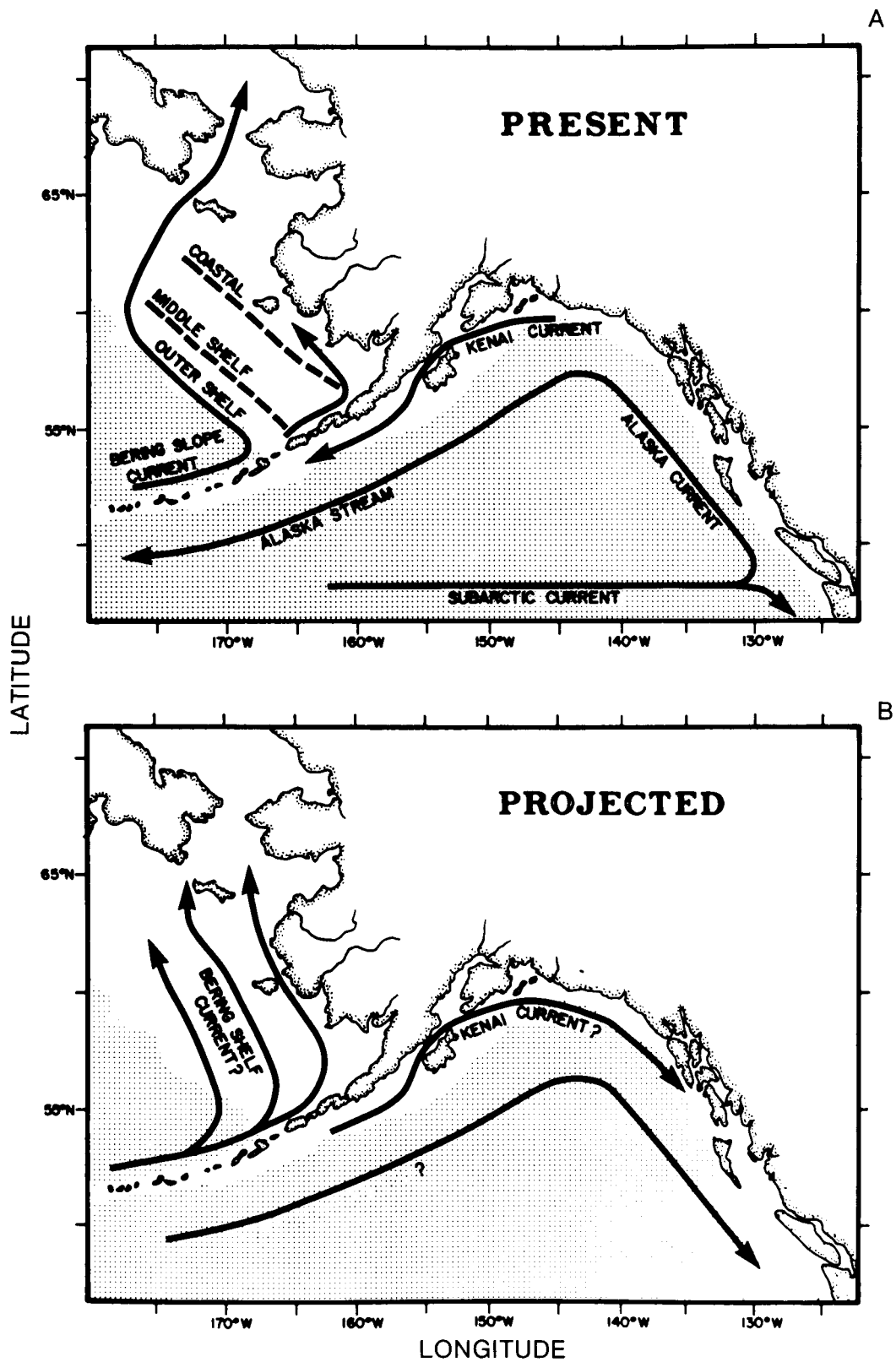


Figure 5.9. Present circulation in the northern North Pacific Ocean and eastern Bering Sea (modified from Favorite et al. 1977) and possible future current patterns under a sustained atmospheric warming scenario involving a consistent northward shift of North Pacific atmospheric pressure centers.

flagellate abundance would be anticipated only in local stratified embayments of the Pacific. These potential shifts in phytoplankton species composition should improve the food supplies of the case study fish, although these food-web interactions are still poorly studied.

The major prey for the life cycle stages of the case study species that feed in the water column (all stages of herring and pollock and the larval stage of sole) are herbivorous zooplankton or small fishes that feed on herbivorous zooplankton. Increased water temperatures would not be expected to shift the species composition of the zooplankton significantly because there are no strong latitudinal gradients in the coastal zooplankton assemblage. However, increased temperatures and the projected changes in phytoplankton species and productivity would alter the seasonal abundance and growth rates of these zooplankton. Furthermore, these increases might not be uniform for all zooplankton species. Therefore, the availability of the most abundant prey for larval and juvenile fish will change.

Differences in zooplankton abundance will be most evident in the eastern Bering Sea, where an assemblage of large, spring-spawning crustacean zooplankton (predominately copepods and euphausiids) that eat both diatoms and flagellates dominates the outer shelf and oceanic waters. An assemblage of smaller, summer-spawning copepods that eat smaller flagellates dominates the middle and inner shelf domains. The few data available on coastal zooplankton of the Gulf of Alaska suggest a similar pattern. The larger zooplankton would benefit more from an increase in the relative abundance of diatoms in both regions, but in the Bering Sea the projected increase in primary production during summer also could benefit the smaller animals. Changes in zooplankton size spectrum could be important because of the prey size selectivity of larval, juvenile, and adult herring, and larval sole.

Pink shrimp and juvenile and adult sole are demersal and prey on smaller animals that are demersal or benthic (living on or in the bottom). These prey consume mostly detritus (nonliving organic matter) derived from plankton remains that sink out of near-surface waters. Increased primary production would generally benefit these bottom-living species, as would increases in temperature. Apart from the absolute magnitude of primary production, however, a higher proportion of surface production appears to reach the bottom when the phytoplankton assemblage is dominated by nonmotile diatoms rather than by flagellates, which are motile and can avoid sinking. A relative increase in the food supply to the benthic community also is believed to occur when there is a "mismatch" in temporal abundances of phytoplankton

and zooplankton, such that few animals of the proper species are present to consume the plants, which sink to the bottom. This situation may explain the dense stocks of demersal fish and shellfish in the middle shelf domain of the eastern Bering Sea and may also be applicable to the isolated, stratified regions of the coastal Gulf of Alaska where abundant bottom fisheries are found. Thus, it appears that climate warming would both enhance the overall primary productivity of the study area and affect the relative fractions of that production that are available for consumption by different fish species.

5.3.2.4 Higher Trophic Levels

Animals that eat fish are generally larger, longer lived, and more mobile than their prey, with greater adaptability to changes in the environment. The best-known predators in the four case study species are larger fish and marine birds and mammals. Invertebrate predators that feed on eggs and larvae may be more important but their significance has not been well defined. Birds feed mostly in the upper mixed layer on eggs, larvae, and juvenile fish, and on adult fish in the herring size class. Some birds also feed heavily on zooplankton. The mammals that feed mostly on zooplankton and small fish include baleen whales; toothed whales and seals feed on fish and shellfish. Predatory losses for any species will be determined by the distribution and abundance of predators and by physical factors that affect trophic interactions.

Climate warming should increase the growth and development rates of cold-blooded immature fish more than those of their warm-blooded predators. Therefore, the duration of vulnerable life cycle stages should decrease and the ability of the fish to escape predation should increase. Conversely, warming would decrease reproductive stress on birds and mammals, especially those that rear their young on shore, such as seals and shorebirds. Thus, predator populations should increase. Little is known about abiotic effects on these predators. The most important potential effect of abiotic environmental changes may be changes in the relative distributions of prey and predators. These effects would be small in the northeastern Pacific compared with those in the eastern Bering Sea, where ice cover has a major effect on animal migrations. In addition to acting as a simple physical barrier to submarine feeding, ice cover limits the distribution of most of the major bird and mammal predators in the region (although such animals as walruses and bowhead whales are ice-edge residents). Extremely cold bottom water that remains over the shelf even after the ice retreats is a barrier to the shoreward migration of deep-

living adult fishes. Reduced ice cover in the eastern Bering Sea shelf would permit a significant expansion in the seasonal ability of all species to migrate northward and into shallow water. This should increase the exposure of fish species to predation.

The increased availability of fish should benefit mammals more than birds in the eastern Bering Sea. Bird feeding, especially that by surface-feeding birds (such as kittiwakes) as opposed to diving birds (such as murres), is sensitive to surface turbulence. Increased storminess and decreased vertical stability in the Bering Sea are associated with reproductive failure of kittiwakes and could offset some of the increased exposure of fish to bird predation. Turbulence in the Bering Sea also could disperse prey aggregation and hamper the ability of mammals to feed on juvenile fish and adult herring in the surface layer. Increased stability in the northeastern Pacific, however, could enhance predation in that area.

5.3.3 Projected Effects on Case Study Fisheries

The expected effects of abiotic and biotic changes discussed above on the case study fisheries are presented in Table 5.3. Only *partial* fishery effects of environmental changes are presented in Table 5.3; possible interactions among climate effects or the sum of their effects are not presented. For example, if increased turbulence decreases both feeding by and predation on a case study species, we do not assess the net affect of these counteracting influences on abundance.

5.3.3.1 General Effects on All Species

The latitudinal distributions of all four species are projected to shift significantly to the north as a result of warming. In the Bering Sea, at the northern limits of their present ranges, species will migrate into and colonize shelf territory that is currently inhospitable because of ice cover. Projecting possible colonization of the Chukchi and Beaufort Sea shelves north of the Bering Strait is highly speculative, however. Because adults now overwinter in ice-free deep water beyond the continental shelf, maximum seasonal ice cover would have to retreat beyond the broad Arctic shelf edge for resident populations to become established. Larvae and juveniles are found under seasonal ice and may be able to use the Arctic seas as nursery areas. It is believed that pollock colonized the Bering Sea from the Atlantic by way of the Arctic during warmer periods in the Pleistocene, and a similar scenario may be reasonable in the future.

Figure 5.10 presents a possible scenario for a shift in geographic distribution of the case study species. It compares the existing commercial ranges of the

four species to the latitudinal distribution of mean seasonal sea surface temperatures at coastal stations. It then superimposes estimates of zonally averaged mean annual sea surface temperature increases derived from estimates by Revelle (NRC 1983) for an equilibrium doubling of CO₂ levels and projects the associated latitudinal shifts in species distributions. This is a highly simplistic projection because it does not consider turbulence, currents, or seasonal differences in estimating temperature changes. Furthermore, it assumes that fish distributions are directly correlated with sea surface temperature, neglecting other important abiotic and biotic factors. Nevertheless, such a scenario suggests the extent of change in biogeographic range that may occur. If the case study species shift to the north, they probably will be replaced by more southerly sibling species that could sustain the fishery. For example, pollock might be replaced by Pacific hake (*Merluccius productus*) and shrimp by *Pandalus jordani*.

Shifts in distributions, if they occurred, might be traced to shifts in major oceanographic features, such as the Subarctic Current (Figure 5.9) or to shifts in surface isotherms. Both herring and shrimp populations are composed of multiple, genetically distinct substocks with separate and fixed spawning grounds. Shifts in the relative latitudinal abundances of these species will most likely arise from changes in the populations of these existing stocks, rather than from migration. Such projections do not take into account, however, genetic adaptation of fishes to gradual temperature changes. If changes are sufficiently gradual these stocks may be able to adapt and maintain themselves. There are few historical data on which to base extrapolations of the possible importance of such adaptation.

Within the latitudinal range of each species, growth and development rates of all four species will increase with increasing temperature, and spawning dates will be earlier. Growth effects will be much smaller on life stages that do not inhabit surface layers (adult pollock, all stages of shrimp, juvenile and adult stages of sole). Predator avoidance due to increased maturity rate and mobility of immature stages is cited most often as the possible dominant effect. However, several other mechanisms could have equal importance for larval and juvenile survival: (1) changes in food abundance or desynchronization of fish spawning times and development rates relative to the development rates and seasonal abundance of prey (match/mismatch); (2) disruption of the surface nursery layer; and (3) changes in horizontal transport.

Individual climatic responses that depend on differences between case study species are examined next.

Alaska pollock. Patterns of abundance and behavior (especially spawning behavior) of Alaska pollock differ

Table 5.3
Potential Climate-Related Effects on Case Study Fisheries in the
Northeast Pacific Ocean and Eastern Bering Sea

Abiotic Effects	Effects on Fisheries			
	Alaska Pollock	British Columbia Herring	Alaska Pink Shrimp	Bering Sea Yellowfin Sole
Increased Water Temperature	<i>Colonization north of present range, possible replacement by competitors to south.</i>	<i>Increase in northern stock, decrease in southern stocks.</i>	Same as pollock	<i>Colonization north of present range; effects on southern range uncertain.</i>
Surface Temperature	Increased growth, development, and mortality rates of eggs, larvae, and juveniles. Increased feeding ability and predator avoidance by larvae and juveniles. Increased and earlier growth of plankton food supplies.	Increased growth and development rates of eggs, larvae, and juveniles. Same as pollock. Same as pollock. Deeper and more northerly adult migration, earlier and possible deeper spawning.	Negligible	Increased growth and development rates of eggs and larvae. Increased feeding ability and predator avoidance by larvae.
Bottom Temperature (Bering Sea)	Increased adult growth rate; earlier and more extensive migration and spawning; altered egg, larval, juvenile, and adult distribution and <i>increased fish predation and cannibalism.</i>	NA	Increased growth and development rates of eggs, larvae, juveniles, and adults. <i>Increased fish predation.</i>	Increased growth and development rates of juveniles and adults. Earlier and more extensive migration and spawning; altered egg, larval, juvenile, and adult distributions and <i>increased fish predation.</i>
Decreased Ice Cover (Bering Sea)	<i>Increased bird and mammal predation.</i>	NA	Negligible	<i>Increased mammal predation.</i>
Decreased Nearshore Surface Salinity	Negligible	Increased size and development rates of eggs and juveniles, possible osmotic stress on larvae.	Negligible	Negligible
Surface Stability Increase in Pacific	Increased feeding ability of larvae and juveniles. Increased, earlier growth of plankton food supplies. Increased feeding ability of predators on eggs, larvae, and juveniles. Possible decreased feeding ability of cannibals. Decreased egg mortality	Same as pollock. Increased feeding ability of predators on larvae and juveniles. Decreased egg mortality	Changes in feeding ability and food supply uncertain. Same as pollock.	NA

Table 5.3(continued)

Effects on Fisheries				
Abiotic Effects	Alaska Pollock	British Columbia Herring	Alaska Pink Shrimp	Bering Sea Yellowfin Sole
Decrease in Bering	Decreased feeding ability of larvae and juveniles. Spring decrease and summer increase in plankton food supply. <i>Decreased feeding ability of bird and mammal predators on eggs, larvae, and juveniles; increased egg mortality.</i>	NA	Changes in feeding ability and food supply uncertain.	Decreased feeding ability of larvae. <i>Possible decreased pelagic detritus food supply to benthic forage prey species.</i> Decreased feeding ability of predators on larvae.
Currents				
Decrease in Pacific	<i>Possible decreased downstream loss of egg, larvae, and juveniles.</i> Possible decreased metabolic cost to adults.	Same as pollock	Negligible	NA
Increased Coastal Upwelling in Pacific	<i>Increased and earlier plankton food supply.</i> <i>Possible increased seaward loss of eggs, larvae, and juveniles.</i>	<i>Same as pollock</i>	Effects on food supply uncertain.	NA
Increased Coastal Runoff in Pacific	Possible increased downstream and decreased seaward loss of eggs, larvae, and juveniles.	<i>Possible increased downstream and seaward loss of eggs, larvae, and juveniles.</i>	Negligible	NA
Increase in Bering	Possible northward and landward displacement of eggs, larvae, and juveniles. Possible consequences for food supply, predation, and cannibalism. Possible increased metabolic cost to adults.	NA	Negligible Possible consequences for food supply.	Possible northward and landward displacement of larvae. Possible consequences for food supply and predation.
Possible Disruption of Fronts in Bering	Possible disruption of food aggregations for species and predators; decreased feeding and predation.		Same as pollock	Same as pollock

Note: These represent *partial* relationships between case study fisheries and the abiotic and biotic environments. Interactions between these effects are considered unknown. Italics indicate projected dominant effects.

NA = Not Applicable

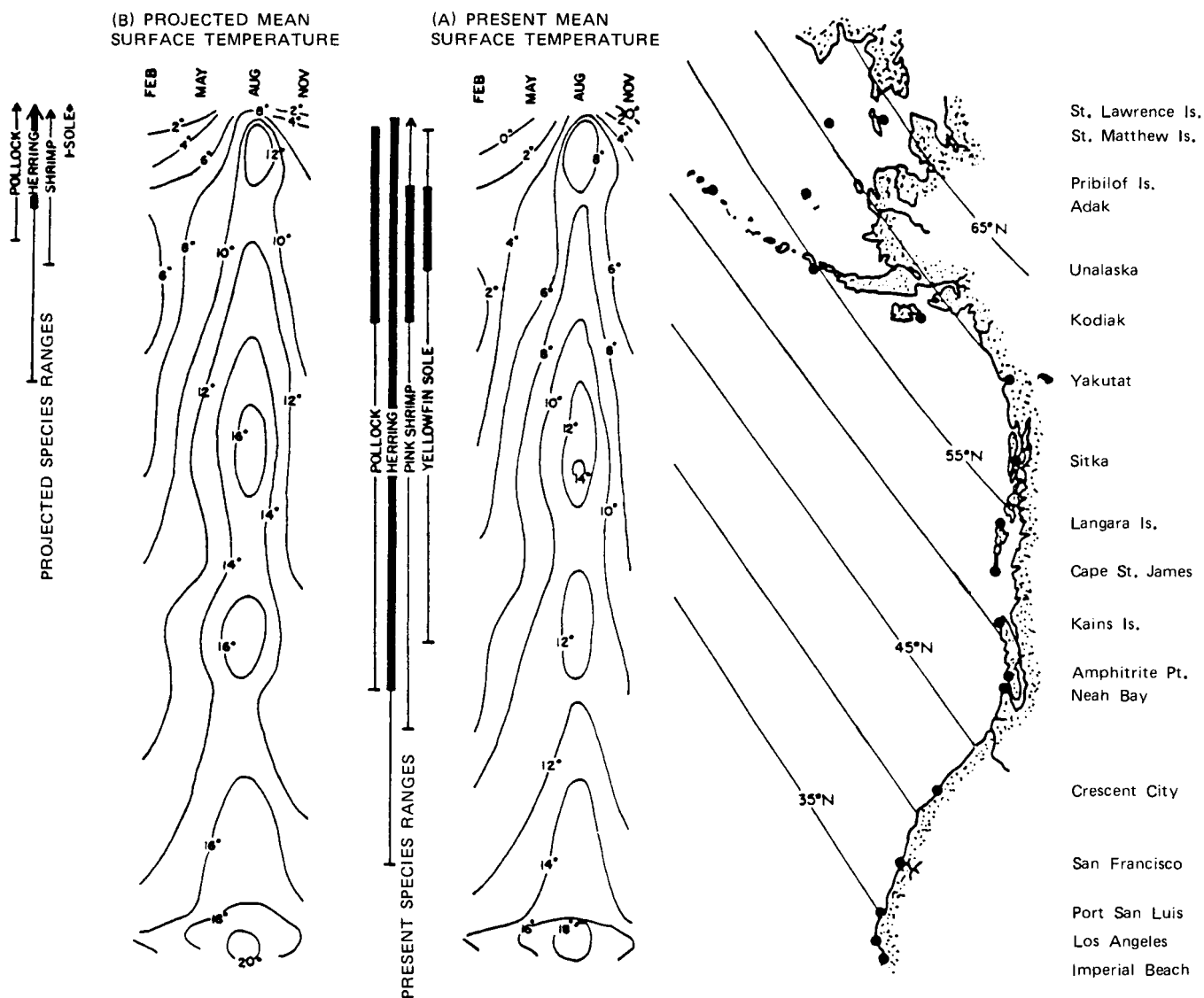


Figure 5.10. (A) Mean seasonal sea surface temperatures from coastal stations in the northeast Pacific Ocean (1948–1975, McLain 1979) and from shipboard data in selected grid squares of the eastern Bering Sea (1953–1982, Ingraham 1983) plotted with the approximate latitudinal ranges of the four case study species (light lines = extremes of ranges; heavy lines = commercial ranges). (B) Projected mean seasonal sea surface temperatures under a CO₂ doubling scenario, obtained by adding to (A) one-half of the zonally averaged latitudinal increases in surface temperature derived by Revelle (NRC 1983) for CO₂ plus trace gases. Warming was assumed to be uniform through the seasons, rather than greater in winter as currently projected, and no attempt was made to consider possible zonal variations in warming at a given latitude related to changes in currents (e.g., Figure 5.9) or turbulence. Projected corresponding changes in latitudinal ranges of case study species represent a probable “worst-case scenario” because they are plotted subject to several important simplifying assumptions. Distributions are assumed limited only by summer maximum temperatures, neglecting possible genetic adaptation and excluding probable changes in other abiotic and biotic factors such as transport, turbulence, prey, and predators. Furthermore, possible replacements of these species by other commercial stocks are not represented but are considered very likely.

between the eastern Bering Sea and the Gulf of Alaska, suggesting that factors controlling abundance and responses to climate are different in the two areas. Evidence suggests that the Bering Sea pollock yield is controlled by interannual variability of cohort abundance determined before age two. Food supplies appear to be adequate for this life stage during warm years, when predation by birds (especially kittiwakes and murre) and mammals (especially northern fur seals), and cannibalistic consumption by adult pollock seem to be the important control mechanisms. Recent data suggest that reduced zooplankton growth or turbulence in cold years could hamper feeding by immature pollock.

Factors controlling pollock yield in the Gulf of Alaska are unknown. An intense concentration of spawning effort over a very narrow time and space range (late March in a narrow band in Shelikof Strait) at the upstream end of a highly advective region suggests that avoidance of advection or synchronization with food supplies could be important for larval survival.

Juvenile pollock in the eastern Bering Sea are believed to be widely distributed under winter ice, where they obtain some refuge from bird and mammal predation and where bottom water, even in summer, can be cold enough to exclude migratory cannibalistic adults. Warming is expected to increase food supplies and make seasonal vulnerability of juveniles to predation and cannibalism more important. Paradoxically, however, increased fishery and predatory pressure on adults could relieve cannibalistic pressure on juveniles and maintain fishery yield, so long as reproductive output is not impaired. These scenarios do not account for the effects of turbulence or currents, however. Turbulence is believed to interfere with prey location by both fish and their predators, but it may also move juveniles downward from their normal habitat to the depth range of adults and thereby increase cannibalistic losses. Differences in current patterns acting on juveniles in different years have been hypothesized to account for differing areal distributions of pollock catch several years later over the continental shelf. Thus, the net effects of climate change on eastern Bering Sea pollock are unclear, but several lines of reasoning point to changes in predation as most likely to affect future abundance.

If the Gulf of Alaska pollock yield is controlled by the effects of food supply and advective loss on juvenile cohort abundance, then warming, with an increase in net southwesterly wind stress, could enhance yield by increasing planktonic food supplies via coastal upwelling, or could affect it through changes in the transport by major coastal currents. It is not clear whether the more favorable nursery habitat for Gulf

pollock larvae is in open water (as in the eastern Bering Sea) or near shore; in the latter case upwelling could aggravate transport losses. Coastal downwelling and increased transport by the Kenai Current have been tentatively linked to greater cohort abundance in nearshore-reared halibut larvae. Predation and cannibalism may also be important to Gulf of Alaska pollock abundance, but fewer data are available to evaluate their role.

British Columbia herring. Although historical data on herring yield are fairly extensive, little progress has been made in determining the factors controlling abundance or in linking observed fluctuations to climate. This difficulty arises partly because the population comprises numerous spawning stocks that are isolated during the egg stage, but increasingly and variably intermingled during later stages, especially during adult migration and in the fishery. Egg and larval stages are believed to be the most sensitive to the environment, but individual stocks experience combinations of general (e.g., weather patterns) and local (e.g., small-scale runoff) environmental conditions that make meaningful correlations difficult. The mortality rate of eggs, which incubate intertidally, is high under all conditions because of wave damage, bird predation, and desiccation at low tide. These factors are believed to be relatively constant, however, and are not regarded as causes of fluctuations in herring abundance. The mortality of larvae is also high, but its causes are uncertain; predation and possible food limitations are poorly quantified. Larval mortality has been associated with offshore transport due to strong local runoff or tidal currents, so that these factors are most commonly cited as potential environmental mechanisms controlling cohort abundance. Increased frequency of northerly winds and offshore transport along the British Columbia coast and increased runoff associated with climate warming both would aggravate these losses, despite increasing food supplies for juveniles and adults. This projected loss would be superimposed on the general enhancement of northern stocks and the depletion of southern stocks associated with physiological effects of temperature.

Alaska pink shrimp. Knowledge of shrimp abundance and ecology in the study area is lacking because shrimp are difficult to sample. This species is unique among the case study organisms in that it remains near the bottom throughout its life cycle. The relative importance of planktonic and benthic food supplies is not clear. Changes in surface temperatures and food supplies might have less impact on shrimp than on other species, although shrimp could be more sensitive to changes in input of pelagic detritus caused by changes in the plankton community. The relationship between

shrimp distributions and bottom water temperatures, especially on the eastern Bering Sea shelf, is unknown. Observed fluctuations in shrimp abundance in the study area are related to fishing pressure and also are suspected of being sensitive to predation by such fishes as cod and pollock. Thus, predictions of shrimp sensitivity to climate change can be no more reliable than those of predator species. It appears that enhancement of shrimp populations in the eastern Bering Sea under climate warming is likely because of habitat expansion and because of predatory limits on fish populations. In the Gulf of Alaska both water temperature increases and fishery enhancement (if other species respond similarly to pollock to warming) could be deleterious for shrimp populations.

Bering Sea yellowfin sole. Yellowfin sole once produced the highest yield of commercial fish from the eastern Bering Sea, but a decline in yield ascribed to overfishing has caused a relatively low catch since the mid-1960s. The stock currently has recovered to its original abundance, and it may be possible to observe intrinsic environmental sensitivities of the species in a relatively undepleted condition. Like shrimp, yellowfin is a benthic animal that is relatively insensitive to changes in the sea surface environment, except for its planktonic larval stage. It migrates into the coastal domain of the eastern Bering Sea, however, where strong vertical mixing produces hydrographic conditions that are uniform with depth to the bottom and could have some effect on benthic populations.

Yellowfin could experience a change in food supply resulting from changes in the planktonic community. Yellowfin prey such as bivalves and polychaete worms consume detritus derived from extensive, uneaten phytoplankton populations that grow in the stable ice-melt layer of the middle shelf domain in early spring. Reduced ice cover and increased turbulence in this domain could disrupt this source of detritus, but more likely these would simply distribute its supply more uniformly through the summer.

There are no working hypotheses on factors controlling cohort abundance of yellowfin sole, but some inferences may be made based on results with other species. Several workers have noted high-standing stocks of forage benthos in the northern shelf region of the eastern Bering Sea and have associated them with a lack of predation by bottomfish such as yellowfin that are excluded from the region by cold bottom temperatures. It would seem that this region could be a habitat that would allow significant increases in the extent and abundance of yellowfin under ice-free conditions. These increases would likely be balanced by a corresponding increase in the feeding ability of predators, such as mammals and halibut, over

the entire range. Predation on larvae and juveniles should receive priority as a potential control mechanism. Increased bottom temperatures could affect the timing of shoreward migration of yellowfin juveniles and adults and the resulting distributions of planktonic larvae, and these changes in distributions could alter the effects of predation similarly to the projected effects for pollock. However, insufficient data are available to construct such scenarios. Therefore it must be assumed that, as projected for pollock and shrimp, yellowfin abundance will change in an uncertain manner depending on the opposing effects of habitat expansion and increased predation.

5.3.4 Dominant Climate Factors

Water temperature appears to have the greatest effect on the geographic distributions and migrations of the case study species. General northward shifts are a predictable consequence of climate warming and are expected to be more important in transitional environments such as the Bering Sea, where abiotic changes will be greatest and essentially virgin habitats will be created. Water temperature changes in most cases will be greatest near the surface where they affect pelagic species and the planktonic larvae of other species. Alton (1981) suggested that deeper dwelling species have broader geographic distributions because of the weaker latitudinal temperature gradients of deep waters. It may be argued, however, that pelagic species will be least sensitive to climate change because they already possess wide environmental tolerances associated with the greater variability of their environment. The case studies suggest that the broadest present distribution and the smallest change in range caused by warming would be found for the Pacific herring and that the narrowest latitudinal ranges of commercial abundance and the most significant changes in range would be observed among the demersal species such as yellowfin sole. This contradiction might be resolved by noting that a transitional environment such as the eastern Bering Sea poses ecological challenges that are not present in more hospitable waters. The most significant distributional changes observed in these case studies are mediated by changes in ice cover and bottom temperatures, the most important abiotic factors related to climate change.

The impacts of climate change on turbulence and currents have received less study and are generally more difficult to predict. These factors generally affect the pelagic stages of fish, and any impacts on demersal stages will occur primarily through changes in input of detrital food supply. Several effects have been hypothesized including impacts of stability or turbulence on primary production; dispersion of food

supplies for zooplankton, fishes, and fish predators; and direct mortality of eggs and larvae. The effects also include impacts of changes in advection on downstream and offshore losses of eggs, larvae, or juveniles from favorable feeding habitat and upwelling effects on primary production. Both turbulence and advection are primarily governed by wind stress but may be modified by temperature and salinity gradients that are affected by warming, ice cover, and runoff.

The greatest uncertainty in making projections of fishery response to climate changes arises in the biological interactions between species of fish and their prey, competitors, predators, and disease and parasite organisms. In the present analyses, there is more evidence for the importance of predation than for the other interactions. However, the effect of climate change on biological interactions is almost entirely speculative. Even if the relationships between abiotic factors and single species were quantitatively well understood, these relationships could not necessarily be extended directly to interactive, multispecies assemblages.

Of the abiotic oceanic variables examined, temperature, ice cover, turbulence, and currents are judged to be most important. In relation to monitoring and predicting the response of the abiotic environment to climate change, the former two variables show greater certainty than the latter. Most of the uncertainty in projecting abiotic changes resides in the impacts of changing wind patterns. Cushing (1982) judged wind to be the most important abiotic forcing function to be resolved in understanding climate control of fisheries. Sea surface motion under climate warming will be very sensitive to geographic shifts in present magnitudes and distributions of atmospheric pressure, prevailing winds, and storm tracks. The present qualitative and quantitative relationships of turbulence and currents to wind speed, direction, and variance are better understood than are the potential changes in those parameters that would accompany atmospheric warming.

5.3.5 Extrapolation to Global Fisheries

5.3.5.1 Other Subpolar and Temperate Fisheries

The fisheries considered above represent major types of commercial species and fishery environments. Other regions that might be compared most directly to the case study area are the northwest Pacific and western Bering Sea, the northwest Atlantic and the northeast Atlantic, the North Sea, and the Norwegian Sea region (Figure 5.11). These are regions at similar latitudes

with broad continental shelves and similar species assemblages producing important commercial yields of clupeids, gadids, and flatfishes.

There are, however, several important differences among these environments, which limit the transferability of results. The dominant abiotic features of the Bering Sea are its broad shelf, weak currents, and seasonal ice cover. Its dominant biotic features are intense predation pressure and detrital input to the bottom. The dominant features of the northeast Pacific are strong currents and moderate temperatures. These specific characteristics are not observed in any of the other systems of the Northern Hemisphere. The northeast Atlantic area has a broad shelf with relatively weak currents like the Bering Sea, but populations of predatory birds and mammals are much lower, and warm currents intrude to keep ice cover far to the north.

The northwest Pacific (including the western Bering Sea) and northwest Atlantic regions both have strong western boundary currents (the Gulf Stream and Kuroshio) that shift offshore to the north, and shelf regions of weaker currents fed by cold water from the north and subject to seasonal ice cover. The northern regions of these fishery areas are somewhat similar to the eastern Bering Sea, although again the predation pressure in the Bering Sea appears to be unique. The northwest Pacific contains a more complex arrangement of land and water, including the Japan and Okhotsk Seas; Japanese, Sakhalin, Kurile, and Aleutian islands; and Kamchatka Peninsula. This creates a broader shelf area that is sheltered inshore of the boundary current. Thus, the Bering Sea may resemble the northwest Pacific more than the northwest Atlantic. The supply of detritus to the shelf bottom is not well known in the northwest Pacific, but some recent work has shown a pattern of sedimentation on the eastern Canadian shelf that is similar to that of the Bering Sea (Mills and Fournier 1979).

It is also difficult to extrapolate to other fishery species, even within the same region. There may be significant differences in the ecology of closely related species in the same environment, or the same species in different environments, that produce very different responses to environmental factors. In addition, it is difficult to separate these responses from abundance trends imposed by fishing. Abundance trends of Pacific cod (*Gadus macrocephalus*), for example, are very different from those of its relative the pollock in the same environments, partly because of differences in diet, depth distributions, and life cycles. Likewise, abundance trends, life cycle strategies, and climatic responses of pollock are very different between the eastern Bering Sea and Gulf of Alaska, even though the stocks are almost indistinguishable biochemically. Thus

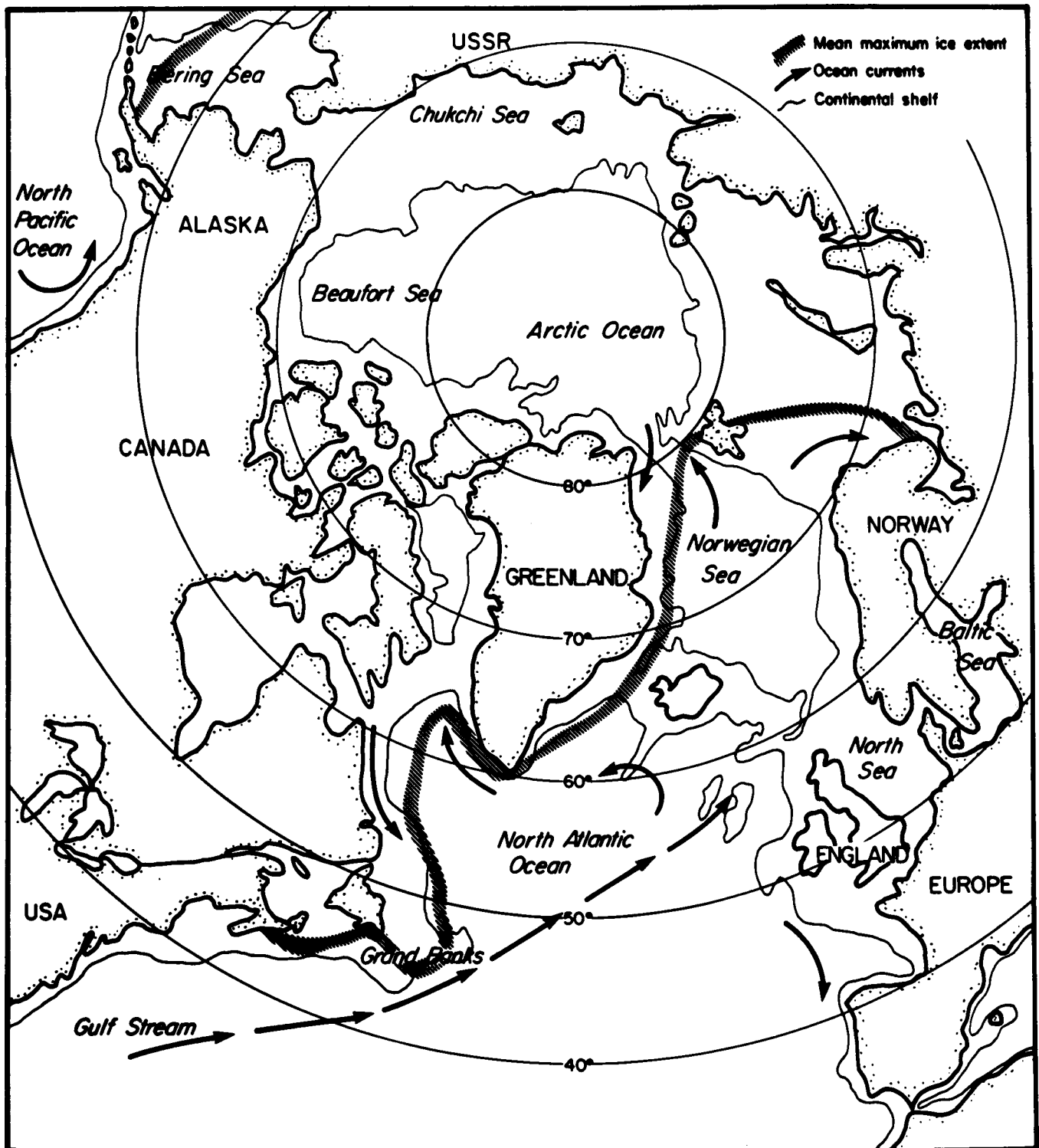


Figure 5.11. Bathymetry, mean current patterns, and mean maximum ice extent of the northern seas. Major fishery zones in both the Atlantic and Pacific regions are found in continental shelf areas of no or seasonal ice cover, which is dictated in large measure by heat transported by currents.

the case study approach for examining climate-fishery interactions may be universally applicable, but results are very difficult to generalize.

5.3.5.2 Other Major Fisheries

This report does not consider the climate sensitivities of other major fishery regions of the world. There are several categories of fisheries that possess very different properties than the case studies. They include temperate and subpolar fisheries in the Southern Hemisphere open ocean; upwelling; high-diversity, low-latitude; and freshwater fisheries. Each of these has unique ecological properties and importance to global harvests. Climate responses of these fisheries cannot be adequately projected from the present case study results.

Fewer developed fisheries exist in the temperate and subpolar regions of the Southern Hemisphere because of the smaller amount of continental shelf area and the remoteness from population centers. Therefore, there generally are fewer data for use in case studies. Some systems that could be considered similar to the temperate northeast Pacific region may be found in the southernmost regions of Chile, Argentina, Australia, New Zealand, and southeastern South Africa. (Western South Africa and Australia possess upwelling zones, discussed below.) The Antarctic Ocean, the only southern region to be influenced by ice cover, exhibits large populations of predatory mammals and birds similar to those of the Bering Sea, but is highly advective like the northeast Pacific. The Antarctic also is an upwelling region.

Only a relatively small number of fish and small yields are caught on the open seas away from the continental shelf. These waters are relatively unproductive. The principal catch species are highly mobile top predators such as tuna and sperm whales. Some data exist on the variability of yield of such species with environmental changes, but the factors controlling abundance are generally not known. Although tuna are not a large portion of the global tonnage of fish catch, they are one of the most valuable groups of fish.

In contrast, warm water marine fisheries near the continents contribute a percentage of world fish yield comparable to that of northern fisheries and are particularly important to developing nations. These regions include southcentral and southeast Asia, Central America and the Caribbean, and the Mediterranean. The people of the western tropical Pacific region are heavily dependent on fish both nutritionally and economically. Tropical fisheries may be the most difficult to evaluate because of the lack of good data. Although impacts of climate change on the tropics may be less severe than on higher latitudes, our lack of

understanding of these ecosystems and the potential human impact of their disruption makes this data gap very significant.

Upwelling fisheries occur in a wide variety of geographic locations that have a mean or seasonal offshore transport of surface water. These are the most productive fisheries per unit area in the world, and before 1972 accounted for about half of the total global fish yield. Upwelling fisheries occur off western North and South America, northwestern, southwestern, and northeastern Africa, western Australia, and Antarctica. Some of them have been studied extensively and provide some of the best available evidence for climate effects on fisheries.

The decline of the Peruvian anchovy (*Engraulis ringens*), which severely affected the Peruvian economy, has been extensively documented (e.g., Barber and Chavez 1983). It occurred as a combined result of chronic overfishing that diminished the natural ability of the anchovy to maintain stocks and of the meteorological perturbation of El Niño. During El Niño, changes in ocean currents reduce the supply of nutrients provided by upwelling and diminish the production of plankton eaten by anchovies. Fluctuations of such magnitude have not been observed in other upwelling fisheries, but significant variability in upwelling currents and plankton production are recorded (e.g., Chelton et al. 1982; Walsh 1983). Direct effects of currents and turbulence on fish associated with upwelling appear likely (e.g., Parrish et al 1981; Francis and Bailey 1983). Climate effects on upwelling are among the best known and most serious impacts of climate on fisheries. Because upwelling is a consequence of a particular relationship between local wind patterns and coastline orientation, it is difficult to project possible changes in upwelling using climate models that are zonally averaged, without consideration of local or seasonal effects. If such projections could be made, the fishery and economic impacts could be better characterized.

This study did not consider climate effects on freshwater fisheries. Although freshwater yield is only a small fraction of global fishery yield, significant impacts of climate change could be important in many nations, particularly underdeveloped nations that are more dependent on fresh or brackish water fisheries. Freshwater systems may be much more sensitive to CO₂-induced climate changes because they are more susceptible to changes in temperature, pH, and water supply.

Special mention must be made of the potential climate impacts on estuaries. These areas, where rivers enter the ocean, are spawning or nursery areas for large numbers of important commercial fish species, including anadromous species such as salmon and

striped bass (McHugh 1967). Estuaries also support several important commercial shellfish species such as oysters. Like freshwater bodies, estuaries are shallow and are fed by local runoff and may be particularly sensitive to climate-related changes in temperature, freshwater input, and salinity, as well as currents and turbulence. Estuaries also are important areas for human residence and industry, and many are already subject to overfishing and pollution stresses.

5.4 UNCERTAINTIES AND RESEARCH NEEDS

5.4.1 Analysis of Uncertainty

There are three major sources of uncertainty in the preceding analysis. First, global climate models provide inadequate or inaccurate projections of future mean climate conditions, and the resolution of spatial and temporal variability currently is inadequate for making fishery projections. Second, baseline data and knowledge concerning fisheries and their environmental interactions are inadequate in most cases to characterize fishery-climate interactions under present climate conditions. Finally, climate change may generate unexpected or unknown interactions between environmental factors (such as pH, temperature, or predation), or changes in existing interactions that fishery scientists have not investigated. The first two sources of uncertainty, in particular, greatly limit the confidence of our projections.

The greatest certainty is associated with qualitative projections of the likely *direction* of changes, such as projected increases in water temperature and growth rates of fish. Generally there is less certainty in quantitative projections of the *magnitudes* and *rates* of changes, and there is little knowledge about the possible spatial and temporal *variability* of the changes. Thus, these three levels of information tend to fall into the known, uncertain, and unknown categories, respectively.

Table 5.4 presents a generic analysis of known, uncertain, and unknown information relating to fishery-climate interactions. Table 5.4 contains four sections that evaluate uncertainties in (1) the state of fishery methodology, (2) the state of knowledge of climate-related abiotic and biotic environmental factors affecting fisheries, (3) effects of climate change on environmental factors, and (4) effects of projected environmental changes on fisheries. Only the uncertainties associated with individual factors are presented in Table 5.4; *interactions between different factors are all major unknowns.*

The limitations in fishery methodology account for most of the present uncertainty regarding fishery-climate relationships. Data on the abiotic and biotic environments are scarce and expensive, but the methodology associated with obtaining those data is less a limiting factor for fishery investigations than is fishery methodology. The most serious handicaps are the inability to locate and enumerate the early life stages of fish and to evaluate their physiological conditions.

Theoretical knowledge of fishery-ocean interactions also limits the prediction of climate effects, in particular the ability to make quantitative projections and simulation models. Adequate theoretical or empirical equations are available to describe most abiotic effects, such as air/sea heat and momentum transfer, under idealized conditions. It is more difficult to apply several such relationships simultaneously over broad spatial and temporal scales while still adequately representing the small-scale variability that is biologically significant. There also are some useful physiological and ecological equations (e.g., Clarke 1983; Maynard Smith 1974) to represent certain biological behaviors of fish and lower trophic levels—for example, temperature responses and predator-prey interactions—at scales of spatial and temporal resolution similar to those possible for the abiotic environment. Their direct application to fisheries is limited, however, by the lack of adequate theoretical representations of other processes such as effects of turbulence and currents on larval fish mortality.

Detailed analysis of the knowns, uncertainties, and unknowns for case study fisheries is presented by Strickland et al. (1985), and several generalizations may be made. Field data on abundances, distributions, and food-web interactions are usually more available for adult stages because adults are easier to locate and capture. For some species physiological data are available on the early life stages (eggs and larvae) of species for which these stages can be obtained and maintained for laboratory work under nearly natural conditions. Juvenile stages, which are difficult both to sample in the field and to maintain in the laboratory, are least studied for most species. We have greater confidence in our knowledge of abiotic effects on case study species than of biotic effects.

The case study environments and fisheries possess several idiosyncrasies, such as the effects of ice cover, cannibalism, runoff, intertidal spawning, and upwelling that are not well represented by a generic treatment. Extrapolation to other fisheries will be limited by those idiosyncrasies.

5.4.2 Research and Data Needs

Based on the uncertainties in our present understanding of fishery-environment interactions, it is possible to identify data needs and suggest research projects to obtain some of those data. Table 5.5 identifies specific scientific problems regarding the potential effects of climate change on fisheries. The data needs are derived directly from the analysis of uncertain and unknown data, and specific research tasks are presented for filling each of these data gaps.

The general categories of problems identified in Table 5.5 are defined in terms of baseline fishery knowledge and methodology, biological effects of abiotic forcing functions on organisms, and interactions of abiotic and biotic effects. The data needs from the Climate Program of the Carbon Dioxide Research Program are presented in the form of the physical oceanographic parameters that would be used directly in making fishery assessments. In some instances meteorological or other data may be more easily available from the Climate Program and could be used as proxy data if they have reasonably well-understood theoretical or empirical relationships with the oceanographic data. For instance, data on wind speed, direction, and variability might be used to derive biologically relevant patterns of surface water turbulence and transport.

The levels of resolution specified for these abiotic data are somewhat arbitrary because the actual scales of abiotic variability known to affect fisheries are much finer than can be provided by climate models within the foreseeable future. The resolution presented was selected as the coarsest that could provide meaningful biological insight. Temperature sensitivity was selected, for example, to estimate the largest temperature increment that would not produce detectable effects at the most sensitive stages of the life cycle and in the most sensitive regions of the temperature spectrum of the four case study species. For example, the most successful spawning of eastern Bering Sea pollock and pink shrimp is restricted to a temperature span of about 3°C. Therefore, a change of 2°C at either end of this range could significantly affect spawning success.

Spatial scales of resolution were chosen in similar fashion. The 5° × 5° horizontal grid scale is the coarsest that could effectively discriminate major oceanographic or fishery provinces within the study area. This spatial scale separates the northeastern and southeastern Bering Sea, and the eastern, central, and western Gulf of Alaska, all of which are observed to have significantly different yields and reproductive conditions for the case study fishes. This scale corresponds roughly

to that employed for management purposes by the International North Pacific Fisheries Commission.

Finer scale horizontal resolution is required for certain properties, such as sea ice extent in the eastern Bering Sea, for which nearly the entire historical record of variability falls within a single 5° grid square. Shrimp and herring spawning grounds may be discrete patches of a few kilometers, and the relevant spatial scales of surface transport that appear to affect survival of larval herring may be dependent on runoff from individual rivers. If projections of mean runoff patterns (magnitude and timing) under climate warming were available, they might be useful as proxy data for the desired small-scale patterns of water motions when applied at known spawning and runoff sites.

The vertical resolution of surface turbulence and transport data requirements was selected to span the approximate 100-m maximal seasonal range of the surface mixed layer and euphotic zone in subarctic waters. Biologically relevant physical processes such as light absorption and mixing of nutrients, salt, and heat take place in this stratum. The vertical increments for turbulent eddy coefficients were selected as the minimum values necessary to represent seasonal changes in surface mixed-layer depth. Currents and turbulence are most important in the upper 50-m layer, which contains most photosynthetic plankton and sensitive early life cycle stages of fish.

The scales of temporal resolution necessary for biological projections vary considerably through the year, but biologically significant changes in abiotic properties (such as transport in the Gulf of Alaska) can occur over monthly time scales even in winter. During the spring, the necessary time scales for plankton production, survival of fish eggs and larvae, and important abiotic fluctuations are very small. For example, a single storm lasting from a few hours to a few days may significantly affect year-class survival. Such energetic events are poorly represented by averaged conditions, and even weekly observations during critical periods might not reveal these fluctuations. If storms could not be predicted or reliably observed, however, stochastic estimates of the probable magnitude and frequency of such events would still provide biologically useful information.

In addition to surface temperatures, it would be useful to have estimates of bottom temperatures in the study area because these have been shown to affect both migrations of adult fish and survival of demersal shrimp larvae. Bottom temperatures are currently much less variable than surface temperatures and probably will be less affected by climate warming. This may not be the case on the eastern Bering Sea shelf,

Table 5.4
Known, Uncertain, and Unknown Information for Evaluating Generic Fishery-Climate Relationships

Problem	Known	Uncertain	Unknown
What Is Our Ability to Assess Fish Abundance?			
Sampling Methods	Methods for locating and sampling adults. Commercial catches and some scientific surveys. General biogeographic ranges over which species are observed.	Methods for locating and sampling immature stages. Relation of commercial and survey data to abundance. Stock separations and migrations. Interannual variability of adult distributions and abundances.	Spatial/temporal abundance and variability of immature stages. Abundance of noncommercial species, and of commercial species in unfished and unsurveyed locations and seasons.
Physiological Methods	Laboratory methods for growth, maturity, feeding, mortality, and reproductive rates. General relationship of age to length and scale or otolith rings.	Field methods for growth, maturity, feeding, and reproductive rates. Accurate separation of catch by year-class.	Field methods for mortality rates. Correlation of variations in growth increments with environmental mechanisms.
Conceptual Understanding	Fishable biomass integrates strength of several consecutive year-classes above age of recruitment. Year-class strength determined at an early stage of life cycle.	Abiotic (temperature, turbulence, advection) and biotic (food supply, predation) factors that control year-class strength. Whether there is a single "critical age" period for each species.	Relative importance of factors, and of abiotic vs. biotic. Whether year-class strength is controlled by a single factor at a time.
Mathematical Models	Simple two-trophic-level temporal population dynamics models.	Multispecies spatial and temporal higher trophic-level models with some abiotic effects.	Multispecies spatial and temporal trophic dynamic models with complex abiotic effects.
What Is Known About Environmental Control of Fish Abundance?			
pH	Biochemical and physiological responses are pH dependent. pH affects trace metal speciation.	Responses of marine fish to projected changes in pH. Fish response to trace metal concentrations and speciation.	Which chemical species are biologically available.
Temperature, Ice Cover, and Salinity	Laboratory effects of temperature and salinity on physiology of some life cycle stages of some species. General biogeographic and migratory distributions relative to surface and bottom temperatures and salinity.	Laboratory effect of temperature and salinity on most stages and species. Effects of temperature and salinity variations of spatial/temporal distribution of migration and spawning.	Physiological effects of temperature and salinity in the field, including rates of acclimation to temperature and salinity changes. Presence and distribution under ice.
Turbulence and Currents	Eggs and larvae in surface layer are vulnerable to water motions.	Water motions may disrupt or remove eggs and larvae from favorable feeding conditions.	Magnitude and timing of sensitivity; direct mortality from turbulence.
Lower Trophic Levels	Effects of food quality and quantity on feeding and growth of some life cycle stages of some species in the laboratory. Dependence of bottom feeders on surface production.	Diet and growth rates of some stages of some species in field. Effects of turbulence and species composition on surface/bottom partitioning of production.	Occurrence and effects of starvation in field. Effects of spatial/temporal distribution of prey on feeding. Effects of variability of food supply on bottom feeders.

Table 5.4 (continued)

Problem	Known	Uncertain	Unknown
Competitors	Identities and diets of some stages of some species.	Spatial/temporal abundance of competitors and relation to abiotic environment.	Whether resources are limiting, i.e., whether competition exists.
Higher Trophic Levels	Identities and spatial/temporal distribution of some predator species.	Identities of predators on eggs and larvae of some species. Diets, abundance, and metabolic demands of predators. Relations of predators to abiotic environment.	
Diseases and Parasites	Identities and incidence of most parasites and diseases in catch.	Effect of diseases and parasites on mortality and yield at sea. Relations of some pathobiology to abiotic environment.	Relations of most pathobiology to abiotic environment.
How Will the Marine Abiotic and Biotic Environments Be Affected by Climate Change?			
pH	Projected magnitude of change due to increased atmospheric CO ₂ alone. Dependence of chemical speciation of minor elements on pH.	Magnitude of changes given changes in turbulence and currents. Specific factors that currently determine chemical speciation.	Rate and variability of changes. Projected changes in inorganic speciation.
Temperature, Ice Cover, and Salinity	Present spatial/temporal variations relative to weather. Projected direction of changes due to warming alone. Direction of changes given changes in turbulence and currents.	Geological history of variations in distributions relative to past climate changes. Magnitude of changes due to warming. Magnitude of changes given changes in turbulence and currents. Projected direction of changes due to turbulence and currents.	Projected transient and equilibrium variability relative to future climate change. Rate and variability of changes. Rate and variability of changes given changes in turbulence and advection. Projected rate, magnitude, and variability of changes due to turbulence and advection.
Turbulence and Currents	Direction of change due to warming alone.	Magnitude of changes due to warming alone. Direction of changes given changes in wind patterns. Interactions of warming and winds.	Rate and variability of changes due to warming alone. Rate, magnitude, and variability of changes given changes in winds. Projected changes due to wind changes caused by climate change.
Lower Trophic Levels	Laboratory effects of temperature and trace metals on plankton. Mean spatial/temporal distributions of major prey species relative to abiotic factors. Projected direction of changes in spatial/temporal abundance due to warming alone.	Temperature effects on benthos. Effects of salinity, CO ₂ , and pH. Magnitude, spatial/temporal distributions, and variability of production and standing stocks of prey. Projected rate and magnitude and seasonal and areal extent of change in prey production due to warming alone. Assumption that competitors will react similarly to other fishes.	Interactions with other abiotic and biotic effects in field. Abiotic effects on feeding process. Projected changes in pelagic/benthic partitioning of food supply. Variability of changes. Interaction with other abiotic and biotic effects.
Competitors			

(continued)

Table 5.4 (continued)

Problem	Known	Uncertain	Unknown
Higher Trophic Levels	General identities, life cycles, and distributions relative to abiotic factors.	Abundance and spatial/temporal variability. Metabolic demands, diet variability. Responses to abiotic factors. Direction of changes in growth rate and abundance due to warming.	Effects of abiotic variables and warming on feeding. Effects of abiotic variables and warming on trophic interactions. Rate, magnitude, and variability of changes.
Diseases and Parasites			Changes due to climate change
How Will Fisheries Be Affected by Changes in the Marine Abiotic and Biotic Environments Related to Climate Change?			
pH	Projected responses of fish to increase in dissolved CO ₂ .	Projected responses of fish to changes in pH and trace metals.	Interaction of CO ₂ , pH, and trace metal stress with temperature and other stresses.
Temperature, Ice Cover, and Salinity	Direction of changes in growth and development rates, spawning and migration, and latitudinal distributions given changes in temperature and salinity alone.	Rate, magnitude, and timing of changes. Impact of changes on year-class strength and fishery yield.	Variability of changes, and sensitivity to rate and variability of abiotic changes.
Turbulence and Currents	Direction of changes in year-class strength given changes in turbulence.	Direction of changes in year-class strength given changes in currents. Projected direction of changes in year-class strength.	Rate, magnitude, and variability of changes; sensitivity to rate and variability of abiotic changes.
Lower Trophic Levels	Direction of changes in year-class strength given changes in standing stocks of prey.	Magnitude of changes. Effects of possible changes in species composition of food. Projected direction of changes.	Rate and variability of changes Projected magnitude of changes
Competitors		Assumption that competition will remain roughly constant.	
Higher Trophic Levels	Projected direction of changes in year-class strength due to changes in standing stocks of predators.	Magnitude of changes. Effects of possible changes in species and distribution of predators.	Rate and variability of changes
Diseases and Parasites			Changes due to climate change

Note: Uncertainties in *partial* relationships between generic fisheries and the abiotic and biotic environment. Interactions between these effects are considered unknown.

however, because here bottom temperatures are closely linked to winter air temperatures and sea ice extent, which may be altered more than summer air and sea surface temperatures by CO₂-induced warming. Bottom temperatures have been omitted from Table 5.5 because they may be very difficult to model, and because it is assumed that they can be adequately derived from sea ice extent data. However, this assumption may be a poor one in totally ice-free environments such as the Gulf of Alaska and possibly the future Bering Sea.

5.4.3 Suggested Research

Understanding the relationship between fisheries and climate will be limited by improvements in basic fishery science, so that recommendations for climate-related research will strongly resemble those for other fishery questions. Recent workshops (Bakun et al. 1982; Rothschild and Rooth 1982; Wooster 1983) have developed plans for improving basic fishery research, and their conclusions are relevant for climate studies. Although there are some differences in the priorities and details of research recommended by these groups, they agree on several central conclusions:

1. The fundamental problem in fisheries at present is that the extent and the mechanisms of environmental control of fishery year-class strength are unknown.

2. The greatest uncertainty about possible environmental mechanisms is associated with trophic interactions. Predation and starvation both appear to be important. Starvation is suggested by laboratory studies but is difficult to demonstrate in the field, and its main effect might be to increase susceptibility to predation (Rothschild 1982). However, predation is more difficult to monitor, and food supplies appear to be more sensitive to the abiotic environment. Thus, the most important mechanism to study is abiotic control of the spatial and temporal abundance of planktonic prey at "microfine scales" (1–10 m³ and hours to days) and their effects on survival of fish larvae. At this time primary production is both the most environmentally sensitive and the most scientifically tractable segment of this mechanism and should be the focus of research (Cushing 1982).

3. Understanding environmental controls on fish abundance is best served by adopting a new, holistic perspective that integrates traditional fishery surveys with physical and biological oceanography and meteorology. This perspective should include consideration of multiple species of fish and their prey and predators for both scientific and management purposes.

4. Such a perspective also would be best obtained by coordinating parallel research efforts in the field and laboratory with literature and data surveys, and empirical and deterministic methods of data analysis.

Each approach requires interaction with the others to maintain its progress. At this time, theory is adequately developed and needs further input from collection and empirical analysis of field and laboratory data.

5. Several guidelines are suggested for field studies: (a) There is an urgent need for technological advances in sampling, enumerating, and evaluating the condition of immature fishes and their prey at appropriate spatial and temporal scales. (b) Studies at sea ideally should yield real-time synoptic data over scales sufficiently large to reveal features of the scales of fronts and eddies (100–200 km) and storms (2–4 weeks). This will require multiple investigators and probably a reordering of the priorities of funding agencies. (c) At the same time, individual observations should be made at the microfine scale. These data should be supplemented by on-board laboratory experiments on trophic interactions. (d) Such studies should select locations and sampling designs to test hypotheses, rather than routine surveying. (e) However, such intensive studies should be supplemented by long-term routine monitoring at several sites to yield data suitable for time-series analysis.

6. In addition to conventional laboratory studies of physiology in single-species aquariums, there is great opportunity for investigating trophic interactions at the microfine scale in larger enclosures (micro- or mesocosms). Such studies could be conducted on land or aboard ship and could simulate interactions that are difficult to observe in natural systems.

7. Three types of data analyses are useful for interacting with field and laboratory studies. Wooster et al. (1983) recommended that case study literature and data reviews be conducted as part of the planning process for field and laboratory fishery studies. Rothschild (1982) also recommended simulation models as planning tools, as well as companions for mesocosm studies. Bakun et al. (1982) recommended derivation of empirical indices (e.g., Bakun's upwelling index) that could be correlated with fishery parameters in the search for deterministic environmental mechanisms. Rothschild (1982) also cited such empirical analyses as a necessary companion to simulation models, but stressed that correlations alone can never provide proof of environmental mechanisms.

We do not yet know how recruitment to fish stocks is generated or which processes are important for different fish stocks. Because environmental factors must be mediated through recruitment, it is essential to specify these mechanisms. Detailed studies of growth in relation to food availability and of mortality during the first year of life should provide critical information for establishing important processes. Because the sampling interval must be short, a detailed analysis of individual

Table 5.5
List of Data Needed From Climate Program and
Suggested Research to Fill Data Gaps in North Pacific Case Studies

Problem	Research and Data Needs	Data Needed From Climate Program	Suggested Research
1. Baseline Fisheries Methodology			
a. Distribution, Abundance, and Growth of Life Cycle Stages of Fish	Technological, logistic, and statistical methods for locating and quantifying fish populations and growth rate at early ages.		Supplement existing acoustic and trawl surveys, statistical analyses, and research on scale and otolith rings.
b. Methods of Maintaining Life Cycle Stages of Fish in Laboratory	Food, space, temperature, and chemical conditions suitable to survival.		Supplement existing laboratory studies.
c. Effects of Spatial Heterogeneity of Prey on Feeding	Food capture by zooplankton, fish, mammals, and birds under turbulent and calm conditions.		Supplement existing field surveys of gut contents and hydrography. Initiate possible mesocosm experiments.
d. Development of Mathematical Models of Fisheries	How to parameterize physiological and ecological relationships and spatial and temporal variability.	Global and local climate and oceanic circulation models.	Supplement existing research on higher trophic level simulations. Initiate additional research on lower trophic level simulations.
e. Data on Abiotic Environment	Winds, currents, turbulence, temperature, salinity, and pH.		Supplement hydrographic data collection by existing surveys and satellites.
2. Chemical Effects of CO₂			
a. CO ₂ -Induced Changes in Water Chemistry	pH-associated changes in trace metal speciation as affected by temperature, salinity, and trace metal and organic carbon concentrations.	Projected range of post-CO ₂ sea surface temperature within 2°C and salinity within 3 g kg ⁻¹ . Monthly means over 5 × 5° grid.	Initiate factorial laboratory experiments
b. Modification by Turbulence, Advection, and Biology	pH alterations due to vertical mixing, surface transport, photosynthesis, and respiration.	See 1d, 4a, 5a	See 3b, 4a, 4b, 5a, 5b below
c. Effects of Chemical Changes on Organisms	Sensitivity of marine plankton and fish eggs, larvae, and juveniles to pH and trace metals, and interactions with temperature and salinity stress. Stimulation of photosynthesis by CO ₂ .	Same as 2a	Initiate literature summaries of known pH and trace metal sensitivities of plankton and fish. Initiate factorial laboratory experiments (1b).
3. Biological Effects of Warming			
a. Effects of Temperature and Salinity Changes on Fish	Sensitivity of growth, development, and mortality rates of eggs, larvae, and juveniles.	Same as 2a	Initiate factorial laboratory experiments (1b). Supplement existing field research on growth and mortality rates (1a).
	Possible changes in incidence of disease and parasitism.	Same as 2a	Initiate literature summary and possible laboratory experiments. Supplement existing field data collection.

Table 5.5(continued)

Problem	Research and Data Needs	Data Needed From Climate Program	Suggested Research
b. Effects of Temperature and Salinity Changes on Lower Trophic Levels	Application of known physiological effects to field. Relative temperature acceleration of timing of spawning vs. food supply.	Same as 2a Same as 2a, but 2 week means from February to June	Initiate statistical and simulation analysis of existing data for temperature and salinity effects (1d). Initiate factorial laboratory experiments on interaction with CO ₂ (2c). Supplement existing field surveys (1a). Initiate laboratory or mesocosm experiments.
c. Effects of Temperature and Salinity Changes on Higher Trophic Levels	Physiological effects in laboratory and application to migration and survival in the field.	Same as 2a	Supplement existing field surveys of predator distributions and survival. Initiate aquarium experiments.
d. Effects of Ice Cover on All Trophic Levels	Physiological effects of very low temperatures. Effects of ice extent on spatial and temporal distributions and life cycle.	Mean monthly ice extent in Bering Sea within 100 km.	Supplement existing field surveys of distribution of life stages of fish, lower and higher trophic levels (1a).
e. Modification by Turbulence and Currents	Changes in temperature and salinity fields due to water motion.	See 4a & 5a	Initiate simulation analysis (1d) and supplement field surveys (1e).
4. Biological Effects of Climate-Induced Changes in Surface Water Turbulence			
a. Effects of Turbulence During Early Life History of Fish	Direct mortality of eggs and larvae. Effects of dispersal on feeding and predation.	Vertical turbulent eddy coefficients within 1 order of magnitude, density within 1g/kg. Monthly means by 25-m depth intervals in upper 100 m over 5 × 5° grid.	Supplement existing surveys field (1a). Initiate laboratory or mesocosm experiments (1b, 1c).
b. Effects of Turbulence of Lower Trophic Levels	Extent of vertical mixing as it regulates light and nutrient flux for photosynthesis.	Same as 4a. Frequency and duration of storm events (winds over 10 cm s ⁻¹) resolved to 1-week intervals.	Supplement existing field surveys with hydrographic, plankton and sedimentation rate data. Jointly support routine multisite baseline hydrographic and biological monitoring.
c. Effects of Turbulence on Higher Trophic Levels	Sensitivity of predators to water motion and food dispersal.	Same as 4b	Initiate simulation analysis (1d). Supplement existing field surveys of weather effects on predation.
5. Biological Effects of Climate-Induced Changes in Surface Water Transport			
a. Effects of Advection on Early Life Cycle of Fish	Effects of surface transport on distribution, feeding of, and predation on larvae and juveniles.	Mean horizontal current components in upper 50 m to within 10 cm s ⁻¹ ; monthly means in 5 × 5° grid, except weekly means in 1 × 1° grid Feb.-June.	Support existing field surveys of early life cycle distribution, feeding, mortality, growth, and year-class strength (1a, 4b).

(continued)

Table 5.5(continued)

Problem	Research and Data Needs	Data Needed From Climate Program	Suggested Research
b. Effects of Advection on Lower Trophic Levels	Effects of localized coastal upwelling and downwelling on plankton Production and sedimentation.	Mean vertical current component in upper 100 m to within 1 order of magnitude; resolution weekly March-Oct. on 100-km grid inside 2000-m isobath.	Supplement existing field surveys with hydrographic, plankton, and sedimentation rate data. Jointly support routine multi-site baseline hydrographic and biological monitoring. Simulation analysis (1d).
c. Effects of Advection on Higher Trophic Levels	Possible effect of surface currents or associated winds on mammal and bird migrations and abundance.	Same as 5a	Supplement existing field surveys
6. Interactions of Climate Effects			
a. Interactive Effects on Single Species	Interaction of changes in water chemistry, temperature, and motion.		Initiate factorial laboratory experiments on single species of plankton and fish.
b. Interactive Effects on Single Trophic Levels	Same as 6a		Same as 6a for multispecies assemblages of similar organisms at various trophic levels.
c. Interactive Effects on Food Web	Same as 6a		Initiate mesocosm experiments on multiple trophic level assemblages.

Note: Parentheses under "Suggested Research" indicate that progress may be limited by indicated baseline knowledge or methodology.

stocks will be costly. However, it may be possible to study two or three stocks and extrapolate to other fisheries.

Specific recommendations for climate-fishery research can be derived from these guidelines. These recommendations extend from two basic principles: (1) Research will be most effective when it involves multiple approaches; however, verification at sea is the ultimate test of any hypothesis, and overall progress will be determined by that state of seagoing science. (2) The most productive avenue for research on climate-fishery interactions is the same as for general environment-fish interactions: abiotic effects on the availability of prey to fish larvae at scales comparable to the sizes of the organisms themselves, with special emphasis on abiotic control of primary production.

5.4.3.1 *Field Studies*

Many organizations already conduct fishery research at sea. Table 5.6 lists several programs in the case study region that are relevant to future climate research. The organizations responsible for fishery research should be encouraged to adopt the recommendations outlined for seagoing studies. The Processes and Resources of the Eastern Bering Sea (PROBES) and Outer Continental Shelf Environmental Assessment Program (OCSEAP) programs as well as the proposed Fisheries Oceanography Experiment (FOX) program in the Gulf of Alaska are good prototypes because of interdisciplinary cooperation and their selection of specifically targeted areas and organisms. However, they have not examined small-scale trophic interactions or changes in prey abundance. Simultaneous measurements of relevant properties such as dissolved CO_2 , pH, and trace metals also could be added. In addition, support is needed for the establishment of routine time series monitoring stations for climatic, oceanographic, and fishery conditions. Such a time series might include monitoring of selected species of fish and plankton to detect possible poleward shifts in distribution.

5.4.3.2 *Laboratory Studies*

There is currently little laboratory research in the case study region compared with the magnitude of field studies and essentially no research on the microcosm trophic interactions. Such research would be very valuable for climate research because it simultaneously targets the small spatial and temporal scales and the low trophic levels considered most worthwhile for illuminating environmental effects on fish larvae. Microcosm studies also would allow studies of the physiological and trophic effects of increased temperature and dissolved CO_2 , depressed pH, and increased trace metal availability on fish larvae. Garrels and

Mackenzie (1981) concluded that microcosms would be very useful for investigating both the role of carbonate dissolution in the carbon cycle and the possible effects of CO_2 on species compositions of marine communities. Finally, microcosms already have been used to some extent to study factors that might influence the rate of sedimentation of organic matter (e.g., Grice and Reeve 1982), and further research along these lines would be relevant both for food supplies for demersal fishes, and for the global carbon budget.

5.4.3.3 *Data Analysis*

Considerable effort is already directed at analyzing existing fishery and environmental data both qualitatively (i.e., literature surveys) and quantitatively (empirical correlations and deterministic models). Each approach merits further support to provide interaction with field and laboratory studies and to complete our knowledge of climatic effects.

The present literature survey has focused on the northeastern Pacific region and is not representative of major fisheries elsewhere in the world. In particular, tropical and subtropical fisheries and upwelling fisheries might respond to climate change very differently from the case study region. Bakun et al. (1982) stressed that to understand how the environment affects fisheries, case study analyses (including field work) should be performed on low-latitude continental shelf, coral reef, and upwelling fisheries that are important for developing nations. At a minimum a survey of one such system should be initiated. Upwelling fisheries are known to be climatically sensitive but also are the best studied of these ecosystems. An additional case study would be most useful for an ecosystem with an ecological structure very different from that of the present case study region, such as a coral reef or one with a potentially great climate sensitivity, such as a fishery in a monsoon region.

An additional case study also might be undertaken on climatic effects on estuaries because of their importance in the life cycles of many fish species and their probable greater response to climate change. Finally, available knowledge about possible climate effects on fish diseases and parasites has not been compiled. These agents can be very harmful under some circumstances and a review of their climate sensitivities would be very valuable.

Several types of empirical analyses have provided insight into possible mechanisms of environmental control of fish abundance. Examples from the northeastern Pacific include a multiple regression model of offshore transport (Bailey 1981), and empirical orthogonal function and principal component analyses of currents (Chelton et al. 1982) and internal waves

Table 5.6
Recent and Current Research Programs Relevant to Fishery-Climate
Interactions of Case-Study Species in the Northeast Pacific and Eastern Bering Sea

Program Name	Lead Institutions	Research Areas	Funding Sources and Status
IRIS: International Recruitment Investigations in the Subarctic	UW, UA, OSU, NWAFC, PMEL, IPHC, IOS, PBS, UBC	Collaborative exchange of research plans and results to study oceanic effects on fish recruitment.	Multiple
PACLIM: Pacific-American Climate Variability Research	Naval Postgraduate School (Monterey) and USGS (Menlo Park)	Collaborative exchange of research plans and results on climate-related environmental research.	Multiple
SUPER: Subarctic Pacific Ecosystem Research	UW, UA, OSU	Plankton dynamics in the oceanic Gulf of Alaska	National Science Foundation
PROBES: Processes and Resources of the Eastern Bering Sea Shelf	UW, UA, Brookhaven National Lab	Physical and biological oceanography and fishery biology of southeastern Bering Sea continental shelf.	National Science Foundation (completed)
OCSEAP: Outer Continental Shelf Environmental Assessment Program	UW, UA, PMEL, NWAFC	Baseline oceanographic, fisheries, and environmental data related to potential impacts of oil exploration on the Alaska continental shelf.	Bureau of Land Management (completed)
FOX: Fisheries Oceanography Experiment	NWAFC, PMEL, UW, UA, IPHC	Physical and biological oceanography and fishery biology of north-central Gulf of Alaska continental shelf.	National Science Foundation (proposed), NOAA
Columbia River Plume	UW	Physical and biological oceanography of Washington coast, 1961 to 1983	Department of Energy (completed)
Eastern Bering Sea Ice	PMEL, UW, UA	Physical and biological oceanography of ice-edge zone.	National Science Foundation
Resource Assessment	NWAFC, UW, UA	Routine surveys of fish, shellfish and marine mammal distributions and abundances on the continental shelf from California to the Bering Strait.	NOAA
Observer Program	NWAFC	Data collection aboard foreign fishery vessels in U.S. waters.	NOAA
Data Analysis and Ecosystem Modeling	NWAFC, UW	Statistical analysis of field data for management and simulation of fish population dynamics.	NOAA
Resource Ecology	NWAFC, UW, UA	Laboratory and field experiments on fish ecology.	NOAA
Halibut Monitoring	IPHC	Abundance and environmental biology of Pacific Halibut	IPHC
Resource Monitoring	State Fish and Game Departments	Surveys and research on shrimp, crab, salmon, and mammals.	States of Alaska, Washington, Oregon

Note: IOS = Institute of Ocean Sciences, BC; IPHC = International Pacific Halibut Commission; NOAA = National Oceanic and Atmospheric Administration; NWAFC = Northwest and Alaska Fishery Center, National Marine Fisheries Service; NOAA: OSU = Oregon State University; PBS = Pacific Biological Station, BC; PMEL = Pacific Marine Environmental Lab. NOAA; UA = University of Alaska; UBC = University of British Columbia; USGS = U.S. Geological Survey; UW = University of Washington.

(Mysak et al. 1982) as they relate to biotic communities. Existing data bases are limited, but further analyses should be fruitful. An important first step is to identify existing data bases and to examine their potential for empirical analysis. A recent workshop attempted to establish an ongoing compilation and cooperative analysis of data bases among climate researchers in different disciplines; the CO₂ program should encourage continuation of such efforts.

An ultimate objective of both fishery and climate research is to construct deterministic models that incorporate existing knowledge of natural systems and have predictive value. For climate research it would be desirable to develop fishery models that are compatible with global circulation models of the atmosphere and oceans. Various models currently exist that represent parts of fishery ecosystems, but no comprehensive models have been developed and they may not be justified under the present state of fishery science. The DYNUMES model of the Bering Sea (Laevastu 1983) is probably the most comprehensive and includes temperatures, currents, and predators over a large spatial grid. However, DYNUMES does not include plankton production, which was identified above as the most fruitful area for research on environmental control of fisheries. Furthermore, Cushing (1983) has judged that smaller scale, simpler models are more likely to be useful during the next decade. One such model is that of Steele (1974), which includes a simple representation of primary production and its partitioning between pelagic and demersal fishes.

Many localized models of marine primary production have been published (see reviews by Platt et al. 1981; Walsh 1983; and Wroblewski 1983), but there has been little effort at deriving a general set of quantitative relationships that could be integrated with existing climate and physical oceanographic models. Development of a primary production model that is versatile enough eventually to be applied to different ecosystems on a global scale should be a high priority. Such a model could have immediate applications for interacting with seagoing and microcosm studies. If a model of this nature also included parameterization of species composition and sedimentation of organic carbon, it would be valuable for research on the role of marine primary production in the global carbon cycle and its relationship to climate change (e.g., Broecker 1984).

5.5 SUMMARY

Increased atmospheric CO₂ levels will have direct effects on climate and on dissolved CO₂ in the oceans and will have indirect effects on abiotic (physical and chemical)

properties of the oceans. Effects of increased dissolved CO₂ should be minimal, except for the possible effects of increased availability of trace metals. The abiotic effects that are most important for marine fisheries are changes in temperature, ice cover, turbulence, and current patterns in the upper layer of the ocean. In addition to atmospheric temperature, winds are the most important meteorological phenomenon affecting abiotic characteristics. These abiotic changes have biological impacts on fish (especially larval stages) as second-order indirect effects. Equally important fishery impacts may be transmitted via biotic effects on prey and predators of immature fish, and the specific distribution of prey in time and space may be as important as their mean abundance. At this time, the most promising avenue for both general and specific climate-related fishery research is the effects of the abiotic environment on the planktonic food supplies of larval and juvenile fish, especially as mediated by primary production.

Global warming will shift the present latitudinal domains of most fish species poleward, but the magnitude of this shift and of possible associated changes in fishery yield are unknown. Warming at high latitudes should be beneficial for fisheries because of expansion of habitat and food supplies. The uncertainty in these conclusions is related to lack of knowledge of the ways that temperature and other factors regulate fish populations, as well as to uncertainties in the rate and magnitude of changes in the environment. Uncertainty also arises because of differing species characteristics and local factors such as rivers, bathymetry, and ice that make it difficult to generalize among fisheries. Estuaries are particularly sensitive environments because they are most exposed to the effects of changes in both temperature and precipitation. Rapid or intermittent changes in climate conditions (such as El Niño episodes) have greater and more deleterious effects on fisheries than the gradual changes expected from CO₂ increases.

Four northeastern Pacific region case study species were studied to evaluate potential responses to climate change. These fishes (Alaska pollock, *Theragra chalcogramma*; Pacific herring, *Clupea harengus pallasi*; pink shrimp, *Pandalus borealis*; and yellowfin sole, *Limanda aspera*) represent a spectrum of habitats and life cycles among commercially important species, and the northeast Pacific (including the eastern Bering Sea) is relatively well studied and representative of subpolar continental shelf areas that also are important in the North Atlantic. In addition to the general effects of climate, these fisheries have the following specific, climate-related environmental sensitivities: (1) pollock sensitivity to ice extent, cannibalism, and bird and mammal predation in the Bering Sea and to coastal currents in the Gulf of Alaska; (2) herring sensitivity

to waves, desiccation, and probably currents in the immediate vicinity of discrete spawning beaches along the British Columbia coast; (3) the relative insensitivity of bottom-dwelling shrimp to temperature changes; and (4) the probable sensitivity of yellowfin sole to ice extent and to associated changes in food supply caused by alterations in plankton species composition.

Because these unique properties of individual fisheries are as important as the general properties of all fisheries for determining climatic effects, the ability to project the effects of climate change on fisheries without performing detailed case studies is limited. Likewise, it is difficult to extrapolate from the results of the present case studies to other fisheries. These results are particularly inapplicable to other major categories of fisheries, including open-ocean, upwelling, and tropical and subtropical shelf fisheries. Such fisheries should be the focus of additional case studies.

Possible temperature effects on the incidence of disease and parasitism in fish also should be investigated.

Ultimately, greater understanding of the effects of climate on fisheries will depend on improvements in coordinated, large-scale data gathering in the field. During the interim period, useful supporting studies can be performed on the small-scale laboratory responses of fish larvae and plankton to abiotic changes (especially CO₂, temperature, and turbulence), and on developing quantitative relationships using these results and other existing field and laboratory data. In particular, there is sufficient theoretical and empirical knowledge to justify beginning the development of a global marine primary production model, which would have the corollary benefit of complementing global carbon cycle models.

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6. POTENTIAL RESPONSES OF FORESTS TO CO₂-INDUCED CLIMATE CHANGE

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6.1 INTRODUCTION

Natural (unmanaged) forests contain trees of many species and individuals of many ages. Those with closed canopies (i.e., greater than 20% tree-crown cover), covering about one-fourth of the globe and constituting about 90% of the growing stock (U.S. Department of Agriculture [USDA] 1982; p. 88), are of particular interest here. These forests are normally so densely populated that the trees must compete with each other for sunlight, water, and nutrients. Also, tree species use different strategies to obtain the resources to grow and to reproduce in the presence of other trees. As a result, few trees in unmanaged forests ever grow at their maximum potential rate or reach their maximum potential age or size. Thus, most trees grow in the presence of stress, making them sensitive to environmental changes of the kind expected from CO₂-induced climate shifts.

The completion of life cycles among dominant trees in closed forests may be viewed as a three-part sequence (Figure 6.1). First, seeds germinate, take root, and survive as seedlings. Second, the saplings reach the uppermost surface of the forest (the canopy) where sunlight is freely available. Third, the trees survive long enough to reproduce themselves. Attainment of the maximum potential growth during development to maturity (25–500 years) is limited by multiple environmental variables (e.g., light, warmth, water, nutrients). Each variable will differ in importance to trees during each life stage and in each species (cf. Figure 6.1a and 6.1b). As a result, the point in life cycles at which CO₂-induced climate changes may affect tree growth will vary from one species to another, as well as from one place to another within the geographic range of each species.

The response of forests to CO₂ effects is important to biospheric processes and economic systems. Forests cover 35–40% of the Earth's surface (Rodin et al. 1975, Olson 1975), produce 65% of the annual carbon fixation (net primary productivity) (Whittaker and Likens 1973), and store over 80% of the world's organic carbon (Olson et al. 1983).

Forests constitute the only source of lumber, the largest source of paper, and a source of many chemicals (Panshin and De Zeeuw 1964). Of the 4.3×10^{11} m³ of softwoods in the world, 4×10^{11} m³ grow in mid- to high-latitudes of the Northern Hemisphere (Soviet Union, 2.6; Europe, 0.3; North America, 1.1×10^{11} m³ [USDA, 1982]). Atmospheric CO₂ effects on climate are expected to be greatest in these regions (Manabe 1983). In contrast, the 8×10^{11} m³ of hardwood growing stock is concentrated in low latitudes of both hemispheres (6.9×10^{11} m³ in Latin America, Africa, and Asia-Pacific regions; Table 6.1). About 80% of the 5.3×10^9 m³ of nonfuel wood timber production in 1977 was consumed by the industrialized countries of mid- and high-latitudes in the Northern Hemisphere: United States, Europe, Soviet Union, Japan, and Canada. Regions other than these consumed over 87% (3.9×10^9 of 4.4×10^9 m³ globally) of the fuel wood production in 1977 (USDA 1982).

Mixed-species and mixed-aged natural stands make up the dominant portion of timber resources rather than intensively managed tree plantations. In the United States, for example, about 4/10 of 1% of forest land is planted annually (USDA 1982), with most of the remaining growth derived from internal regeneration or from natural reforestation following wildfires, floods, windstorms, insect or disease epidemics, logging or agriculture. Although forestry is more intensively prac-

Table 6.1
Harvest of Roundwood in Relation to Growing Stock in the World,
by Softwoods and Hardwoods and by Region and Country in 1973

Region or Country	Total Roundwood Harvest ^a			
	Softwoods		Hardwoods	
	Total (Millions m ³)	Proportion of Softwood Growing Stock (Percent)	Total (Millions m ³)	Proportion of Hardwood Growing Stock (Percent)
North America	379.4	1.6	99.1	1.1
Latin America	45.3	2.0	229.4	0.3
Europe	212.4	2.5	107.6	2.0
Africa ^b	11.3	13.3	300.2	0.5
Asia-Pacific (except Japan)	127.4	2.5	563.5	1.9
Japan	25.5	2.5	17.0	2.0
U.S.S.R.	320.0	0.5	65.1	0.5
Total	1121.3	1.1	1382.0	0.7

^aIncludes fuel wood and industrial timber products.

^bIncludes the Near East.

Source: U.S. Department of Agriculture (1982).

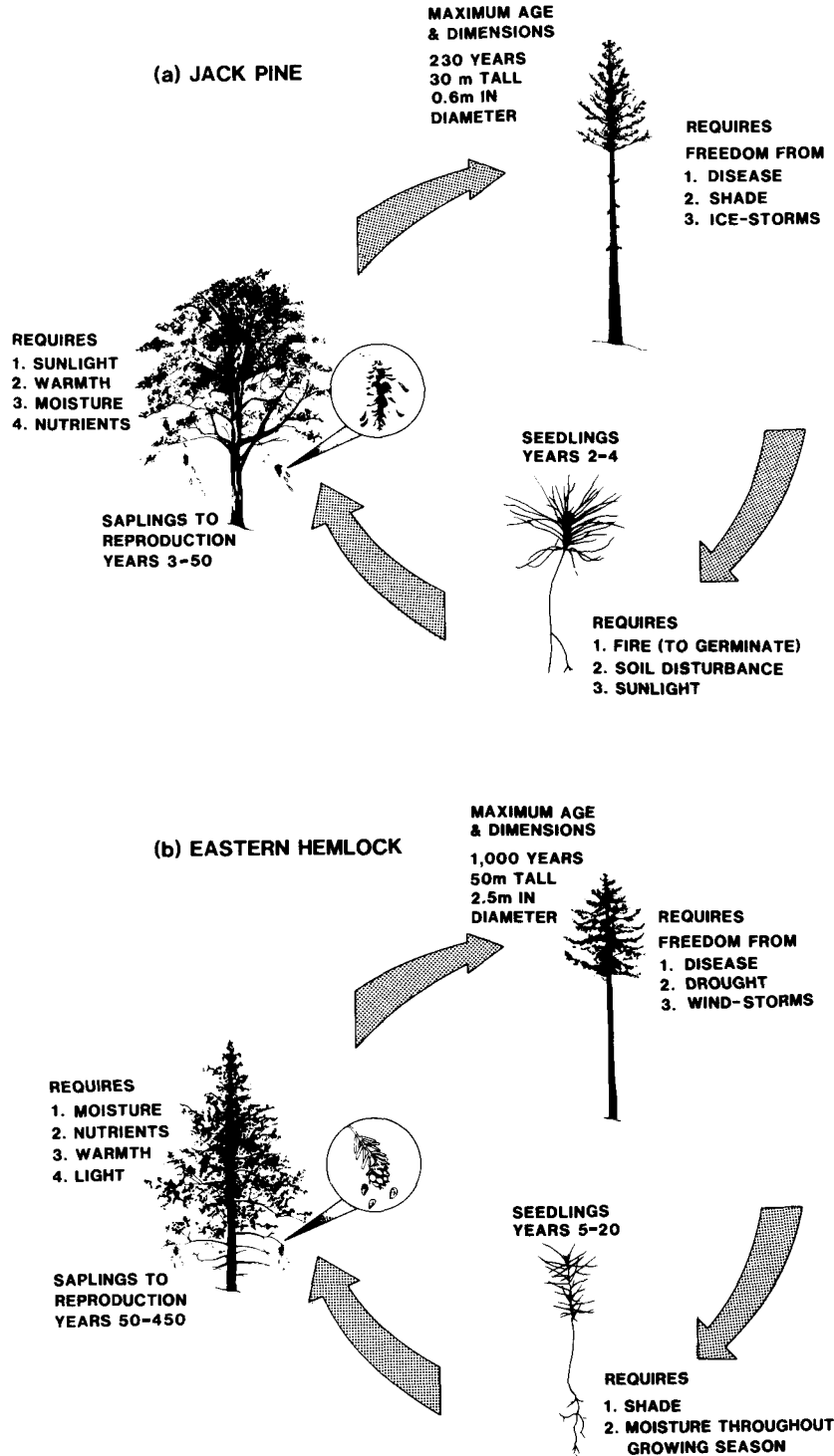


Figure 6.1. Three stages of tree life cycles for two species and the most important requirements for survival and growth during each life stage. The requirements are listed according to priority; hemlock seedlings are limited most by lack of shading; whereas jack pine seedlings are limited most by the absence of disturbed (burned) soil.

practiced in other parts of the world (e.g., Norway, Japan), the total area of the globe's forests derived from plantings was about 3% of the closed forest area in the mid 1970s (USDA 1982; p. 98). Indeed, only one-third of the world's forests have even been inventoried (USDA 1982; p. 88).

Forestry constitutes the seventh largest industry in the United States in product shipment values. It is composed of more than 35,000 companies employing 1.2 million workers. Shipments by these companies were valued at \$79.5 billion in 1976, about 6.7% of all U.S. manufacturing (National Forest Products Association [NFPA] 1980). All economic sectors associated with forest products employed 27.5 million people and added over \$324 billion to the United States economy in 1972 (USDA 1982).

Despite its size and diversity, the timber products industry, which transforms the potential of forest resources into realized economic resources, is unstable (NFPA 1980). It must respond quickly to changes in legislation, product demand, technology, and economic variables such as interest rates, which indirectly control production by affecting timber demand (e.g., the housing industry) and which directly control production through the costs of timberland and postharvest forest regeneration (Miller et al. in press; Rose et al. in press; Woodman in press).

In addition to these realities of long-term capital investment, the characteristic small-business nature of the 35,000 timber companies produces other resource limitations. Thus, an industry that depends upon 30- to 50-year cutting cycles also depends on long-range planning that rarely encompasses over 10 years (Woodman in press). The planning functions (1) to retain enough flexibility to liquidate current forest-land holdings quickly and to obtain new lands; (2) to shift to new product forms rapidly (Rose et al., in press); and (3) to avoid long-term commitments, for example, for successful reforestation of harvested stands that may be mandated by local or state legislation (Woodman in press).

The single point of agreement by attendees of a recent conference to examine the effects of CO₂ on the forest industry (Shands in press) is that estimates of future forest responses to CO₂ and/or to CO₂-induced climate changes must be quite specific if these estimates are to be useful to the forest industry. Generalizations about increased global temperatures or responses of large ecosystems to climate change do not apply well to management decisions on harvest timing or replacement species on, for example, a 100 ha forest plot of mixed Douglas fir, Jeffrey pine, white fir and sugar pine on a north-facing slope in the southwest Oregon Cascade Mountains. Instead, projections must include

the effects over time and by region on seedling survival and establishment and on sapling and mature tree growth. The projections must also estimate geographic implications of effects relating to changes in rotation periods, to preharvest forest treatments (fertilization, precommercial thinning, etc.), to the specific geography of production facilities and markets, and so on. In the absence of such forecasts, the industry alternative is to move or modify operations as changes occur. Thus, the rate of environmental change, and its identification within natural environmental variability, is critical to the maintenance of industry options.

How efficiently the forest products industry responds to tree growth changes brought on by increasing atmospheric CO₂ will depend on how reliably and precisely future forest responses can be projected. The rest of the chapter considers this topic by reviewing the current knowledge, uncertainties, and unknowns relevant to predicting the indirect effects of CO₂-induced climate change on forest communities.

First, the information required from studies of the global carbon cycle, CO₂ effects on climate, CO₂ "fertilization" effects on plant growth, and indirect effects of changing climate on plant growth is considered (Section 6.2). Then, modeling approaches currently available for defining issues and documenting research needs in forest community responses to changing climate are reviewed (Section 6.3). The analysis concentrates on responses by the variable-aged and multiple-species forests, which comprise 97% of the globe's closed-canopy forest resource, rather than on the homogeneous-aged monospecies plantations used in intensive forest management. The final portion of the report summarizes the most critical research needs revealed from examination of the literature and the modeling experiments.

6.2 ISSUES IN PROJECTING FOREST RESPONSE TO CLIMATE CHANGE

Theoretically, some maximum tree density is possible at all terrestrial locations. This maximum density, however, will result only if tree species that are the most efficient competitors for resources reach optimum growth, which, in turn, is possible only if there is adequate sunlight, warmth, soil moisture and drainage, and nutrients during the growing season; freedom from attack by insects, fungi, and bacteria; absence of spring and fall frosts; lack of atmospheric pollutants; and lack of windstorms, ice-storms, floods, and fires.

In practice, however, these environmental factors almost always depress tree growth and favor alternate species that can grow well under the suboptimal

conditions. To grow well, the alternate species may use resources less efficiently, thereby decreasing the maximum potential tree density (biomass per unit area) that a site can support. Climate change due to increased atmospheric CO₂ may induce the suboptimal conditions if it occurs rapidly enough, decreasing tree density as well. Such declines may be measurable in mid- and high latitudes where trees respond in many ways to less-than-optimum conditions, but where they all appear to undergo decreased annual radial increment, potentially providing a universal symptom of health (e.g., see Fritts 1976).

The issues involving projection of forest responses to CO₂-induced climate change are subdivided below into those associated with the carbon cycle (expected rates of atmospheric CO₂ accumulation), climate change (general circulation model [GCM] projections), vegetation responses (physiological processes) and ecological responses (forest community dynamics). The order conforms to system responses to CO₂ through the sequence of atmospheric change, climate response, tree response to climate change, and forest community response to changes in tree growth and climate. Initial uncertainties are generally more important than later ones because errors are amplified as they are propagated through the system.

6.2.1 Carbon Cycle Issues

The rates at which atmospheric CO₂ concentrations continue to increase and the timing and amount of significant CO₂ increases (ultimately limited by finite reserves of fossil fuels and forests to be cleared) will determine both climatic responses that control forest dynamics and the hypothesized response of trees to carbon fertilization (Strain and Cure 1985). To produce valid estimates of the atmospheric CO₂ "chronology" of change, research is needed to quantify (1) the likely rates of fossil fuel use and deforestation, (2) the dynamics of oceanic absorption of CO₂, and (3) the role of the terrestrial biosphere in absorbing and emitting CO₂.

6.2.2 Climate Issues

Improvements in spatial resolution of GCM results are perhaps the most important research priorities for assessing forest responses to expected climate change. The GCMs project climate variables at a spatial resolution of 300–1000 km (assuming about 100 km/degree of latitude and longitude at midlatitude, 400–1000 km, Hansen et al. 1981; 300 km, Mitchell 1983; 400–500 km, Manabe 1983; etc.). In contrast, assessing climatic forcing of tree or forest community response on

time scales of decades to centuries requires spatial detail in climate projections in tens of kilometers because most of the relevant responses by trees and forest communities are generated on small spatial scales. The response of tree species to summer drought differs from one border of its range, where such droughts are frequent, to its other border, where such droughts rarely occur (Bassett 1964; Moehring and Ralston 1967). Species can be abundant and generally successful in one area and nearly absent a few tens of kilometers away (Kuchler 1964). Plant succession occurs in response to forest disturbance (Runkle 1981). Even destruction by logging (land-use), fires or hurricanes (natural catastrophes) rarely covers contiguous areas of more than a few hundred square kilometers in a region annually. Given available growth sites, tree species appear to migrate less than 1.0 km/yr (Solomon et al. 1984).

Projecting specific climate variables to which trees respond is another critical need. Few of the most obvious climate variables of biological significance (see Section 6.2.4) have appeared in GCM investigations. The present generation of GCMs simply was not designed to perform the tasks that this assessment requires of them, that is, data generation in terms of variance and realistic geography of (1) frequency and intensity of precipitation, (2) frequency and intensity of temperature extremes, and (3) timing of shifts in these variables. Research is clearly required on a new form of GCM that can deal realistically with much smaller spatial scales, that can estimate variances in addition to means for the primary weather components, and that can estimate transient climate responses to changes in forcing variables (see MacCracken and Luther [1985] for details).

6.2.3 Vegetation Response Issues

If forest ecosystems respond to CO₂ fertilization, they will do so as a function of changing competitive advantages among species. Based on agricultural research on annual crop plants and on short-term experiments with leaves, branches, and seedlings in greenhouses (see Strain and Cure 1985) physiologists suggest trees will benefit from increased atmospheric concentrations of CO₂ (e.g., Lemon 1983).

Yet, research data indicating that long-lived trees growing in forests behave like those in greenhouse experiments are lacking. More fixed carbon may be produced, but over the years, there may not be enough nitrogen and other limiting nutrients to meet the new demand. Photorespiration (respiration mediated by sunlight) may decrease, but it may not decrease enough to offset increases in dark respiration (respiration not requiring sunlight) in response to soil and air

temperature increases. Water-use efficiency (carbon fixed per unit water used) may increase in individual leaves, but the increased load of leaves may not generate different total evapotranspiration per plant. Photosynthesis may be more efficient in the shade, but it may not compensate for the increased shading because of more and thicker leaves. These unknowns require data that only new qualitative and quantitative research results can provide (see Strain and Cure 1985).

Indeed, the opposite response (growth loss) could actually be occurring. Plants acclimate (cease to respond) to increased CO₂ concentrations after several hours or days (Kramer and Sionit in press), casting doubt on the long-term implications of short-term experiments with high CO₂ concentrations. Studies designed to measure changes in growth of trees in forests, hypothesized from changes in acidic precipitation and gaseous air pollutants, revealed that annual tree growth has declined (Johnson 1983; McLaughlin et al. 1983b; Plochmann 1984) despite increases in global CO₂ of 25–30% since about 1850 (Trabalka 1985). Only tree growth at very high altitudes may match that suggested from increased CO₂ for all trees (LaMarche et al. 1984).

These results are not strong enough to resolve CO₂-related scientific issues; instead they determine research needs and priorities. The overall effects of atmospheric CO₂ on long-term tree growth demand extensive and relevant research. New, imaginative research to exploit field situations that include the critical environmental and biotic variables must be planned and funded. For example, atmospheric CO₂ concentrations were much lower during full-glacial time (about 14,000–21,000 yr Before Present) than they are today. Both global temperature and atmospheric CO₂ increased rapidly about 12,000 years ago (see Trabalka 1985). These natural experiments involve response of tree species and of forest communities to changes in climate and in CO₂ concentrations. Reconstructions of prehistoric forest characteristics, combined with simulation models (i.e., Solomon and Tharp 1985; Solomon and Webb 1985) could be used to assess tree species and forest ecosystem responses to different global atmospheric CO₂ concentrations during this period.

6.2.4 Ecological Issues

Ecological issues are inseparable from issues in carbon cycle, climate, and vegetation responses to CO₂ increases. For example, reproductive success determines what trees will be present at a given location in the future (Ecological Issues). Seed source availability along with soil moisture and temperature variance control tree seedling establishment (Curtis 1959; Kozlowski 1971). It is uncertain whether soil moisture and temperature

variance will change in the future (Climate Issues); however, if they do, the amount that the variances will change is unknown. Atmospheric CO₂ concentrations are known to enhance growth of seedlings in greenhouse experiments (Kramer 1981; Lemon 1983), but the experiments have only replicated the high CO₂ concentrations at the forest floor today, not the still higher ones that may occur in the future (Biological Issues). Consideration of these issues may have to await determination of the rate of future CO₂ increase. This, in turn, will depend on societal needs for fossil fuel and forested land and on feedbacks from forest storage or release of carbon, which could retard or accelerate atmospheric CO₂ buildup (Carbon Cycle Issues).

Growth and maturity of established seedlings and the geographic range of tree species (Ecological Issues) depend on the absolute amount and variance of precipitation as soil moisture (Kozlowski 1968, 1982) and on the extremes of temperature (Aikman 1934; Steponkus 1981; Kappen 1981)—none of which are yet projected (Climate Issues). If mature trees behave as do greenhouse seedlings, increased atmospheric CO₂ could change the documented response of tree species to climatic variance (Biological Issues), but data are still to be developed to demonstrate this response. Availability of the nutrients required for tree growth (Bormann and Likens 1979) depends on population and activity rates of decomposer organisms (Ecological Issues), among other things (e.g., quality and amount of litter, species composition of decomposer communities, etc.). Decomposer populations and activity rates, in turn, depend on the status of soil temperature (Swift et al. 1979) and moisture (Chen and Griffin 1966; Wallwork 1970), neither of which can be specified (Climate Issues).

The opposite of growth is senescence and tree mortality. Senescence occurs when tree vigor declines (Bormann 1965), growth of root systems slows (Redmond 1959), and the water and nutrient needs of leaves cannot be adequately met (Kramer and Kozlowski 1979). Chronic mortality is similar to senescence mortality, although it occurs when growth of any tree (not just senescent trees) is slowed in successive or nearly successive years (Staley 1965; Nichols 1968; Karnig and Lyford 1968). At this point the tree can no longer resist normal stresses.

Premature senescence and increased mortality may result if climate changes continuously or if shifts occur in the frequency of temperature and precipitation extremes (Climate Issues). On the other hand, senescence may be postponed and mortality rates reduced if rising atmospheric CO₂ levels enhance annual growth (Biological Issues). The difference between early or late senescence could affect the carbon source and sink properties of the terrestrial biosphere during at least

the next 50–100 years (Carbon Cycle Issues). Present unknowns among carbon cycle, climate, and biological issues prevent us from estimating either the direction or the amount of combined climate and CO₂ effects on senescence and mortality.

Catastrophic mortality is more visible than chronic mortality, but has a similarly complex basis. Forest losses from, for example, wildfires (Komarek 1966), windstorms (Spurr 1956), and floods (Gill 1970) are directly related to local and regional geographic distributions of climatic extremes, which have not been projected (Climate Issues). Pathogen and insect epidemics that cause local or regional extinctions of whole tree populations (Heybroek 1963; Davis 1981a) are thought to be climatically induced (Waggoner 1962; Rotem 1978), but whether there is a connection is uncertain because of the rarity of such catastrophic mortality events (Ecological Issues). Land-use, in generating homogenous age-structures and nearly pure stands of tree species, contributes to the rapid spread of such outbreaks (Carbon Cycle Issues), but much more data than now available are required to quantify and project such effects under future CO₂-induced climate changes.

The rates and outcomes of forest development (succession) are generally known under constraints imposed by current atmospheric CO₂ concentrations, climate variance, species composition of seed sources, and disturbance frequencies, intensities, and areal extents, all of which vary with local and regional geography (West et al. 1981; Shugart 1984). Whether succession rates will slow and local diebacks occur (Solomon and West in press), if the climate changes continuously (Climate Issues), is uncertain. Whether forest management can or will be practiced on a scale necessary to affect outcomes is unknown. It is also not known whether CO₂ will enhance rates of succession (Shugart et al. 1984; West and Solomon 1984) by relieving growth-loss stress (Biological Issues), nor is the future local and regional distribution of climate variance and forest disturbance by wind, fire, and flood known (Climate Issues).

It is also uncertain what species will be available to influence forest succession in the future; primarily because potential migration rates of species can only be guessed (Johnson et al. 1981), and forest management practices have never been applied on such a grand scale (e.g., USDA 1982). Paleocological records document that the rates of range boundary changes among tree species have averaged 100–400 m/yr during the past 15,000 years (Davis 1981b, 1983), but those rates do not apply to a landscape of forest stands isolated by agricultural and urban land uses (Carbon Cycle Issues). The survival of future seedlings produced by currently mature trees is uncertain. Today, sources of seedlings

adapted to projected future conditions grow far to the south (Miller et al. in press). A critical uncertainty is whether these seedlings will be planted and grown in locations to which they eventually will be adapted, although currently these locations cannot be predicted (Carbon Cycle, Climate, Biological, Ecological Issues).

The foregoing discussion is summarized in Table 6.2, which provides a synopsis of knowns, uncertainties, and unknowns that require resolution before the forest ecosystem response to CO₂-induced climate change can be assessed.

6.3 DEFINING ISSUES IN FOREST RESPONSE TO CO₂-INDUCED CLIMATE CHANGES

This section seeks to examine the available approaches for defining the issues and, thus for determining the research needed for the understanding of forest responses to future CO₂-induced changes in climate. The definition of issues and needed research requires models (e.g., conceptual, mathematical) of the essential environmental, biological, and ecological processes. The models used to study the effects of climate on forests are composed of as much relevant knowledge as possible. The results of model trials identify issues that require scientific research by demonstrating how the systems would behave if the models accurately represented the natural systems. There is no all-purpose comprehensive model, but rather a series of models and model approaches, each with strengths and weaknesses relative to the problems to which they are applied.

Two general model approaches are available to project the responses of forest trees to climate change, each based on different assumptions. The first is a pragmatic approach in which correlations among data sets describing potential causes and effects are substituted for knowledge of actual cause and effect processes. The present geographic distributions of climate variables are calibrated with geographic distributions of biotic variables such as the geography of ecosystems, communities, or tree species densities. Future climate variables can be directly replaced with biotic variables, using, for example, statistical regression techniques involving the climate and biological variables (Solomon et al. 1984; Emanuel et al. 1985).

The second approach uses simulation models of the cause and effect relationships (along with empirical relationships where cause and effect are unknown). The objective is to apply basic data and principles (tree-species natural histories, ecological and physiological processes, and environmental variables) to the task of projecting the response of interacting and nonlinear ecological systems to climate change (Solomon et al.

1984; Solomon and West in press). Like the empirical approaches, simulations require estimates of future climate to drive the model experiments.

6.3.1 Empirical Projection Approaches

This approach uses space as an analogue for time. It is based on the presumption that forest community characteristics at specific locations on the present landscape will be analogous to those existing at different locations in the future. The approach is implemented by first matching geographic patterns of climate and vegetation variables on the present landscape. Then, the climate variables expected to follow a CO₂-induced climate change are used as the basis for transforming the vegetation distributions on the modern landscape to distributions on a future landscape. The data required as input include (1) the geographic distributions of trees or communities today, (2) the geographic distributions of climate variables today, and (3) the expected geographic distribution of climate variables in the future.

The most general form of this approach is to map climate variables of known significance to plant growth (e.g., Köppen 1931; Holdridge 1947) and then to remap the climate variables under future conditions. This approach is illustrated elegantly by Emanuel et al. (1985). They assembled a computerized data base of global climate from over 8000 weather stations with data interpolated to a uniform grid of 0.5° by 0.5° latitude and longitude intervals. The climate variables used in the Holdridge (1947, 1964) classification system (annual average precipitation, annual average temperatures above freezing, and the annual ratio of precipitation to above-freezing temperature) were then subdivided into 17 map units, each with an assigned name indicative of the general character of the vegetation.

The entire data set was mapped by computer into the 17 vegetation units to represent present vegetation (Figure 2 of Emanuel et al. 1985). GCM estimates of climate under doubled CO₂ (Manabe and Stouffer 1980) were then used to modify the temperature portion of the climate data set. A second map was drawn of the vegetation units under this doubled CO₂ climate. Map comparisons indicated the critical need to know more about future precipitation patterns and rates of climate change. In the model results, much modeled tundra and boreal forests on the globe were lost, tropical vegetation increased, and grasslands and deserts increased at the expense of forests. This result leads directly to research questions dealing with such topics as the likely shifts in global supply and demand for the softwood timber harvested primarily in boreal forests and for the hardwood timber from tropical forests (see Section 6.1).

The greatest advantages of the above approach include the generation of global maps, which are comprehensive and quantitative, and in which changes in the subcontinental character of vegetation are immediately obvious. The estimate of potential future vegetation distributions for the entire globe makes this work unique and provides a solid structure for implementing model modifications to treat more complicated environmental forcing and biotic responses.

One important disadvantage to this approach is that it classifies climate, not vegetation. The system uses definitions of "vegetation units," which may only coincidentally match actual vegetation boundaries. Where the climate variables thus classified do not also control vegetation distribution, there will be little relationship between the Holdridge maps and vegetation maps. For example, distributions of plants are rarely limited by either annual or average climate variables used in the Holdridge (1947) system, and many of the Holdridge (1964) subdivisions used by Emanuel et al. (1985) do not possess widely accepted equivalent units among actual vegetation. Thus, the approach might be improved for the purpose of examining vegetation response, with data on geographic distributions of recognized vegetation units and climate variables. However, data for classifying vegetation into acceptable, objectively produced ecosystem units is not as universally available as is the Holdridge system data.

Geographers frequently use the coincidence of such physical variables with biotic boundaries (Mather and Yoshioka 1968; Strahler 1969) to infer climatic control of natural vegetation assemblages, as Blasing and Solomon (1984) did with an agricultural species. Solomon et al. (1984) used this method to map distributions of eastern North American forest ecosystems under hypothetical changes in both temperature and precipitation induced by rising concentrations of CO₂ in the atmosphere.

The primary forest ecosystems of eastern North America have been mapped with varying detail by several authors (Shantz and Zon 1924; Braun 1950; Kuchler 1964; Rowe 1977). The latitudinal boundaries of forest ecosystems can be reproduced fairly accurately by their coincidence with isotherms of annual growing degree days (heat summations that provide a measure of both length and intensity of the growing season; Figure 4, Solomon et al. 1984). In comparison to latitudinal boundaries, the mapped longitudinal boundaries (Figure 5, Solomon et al. 1984) are not as accurately portrayed by annual precipitation, probably because the forest-prairie boundary is determined by a complex set of conditions in addition to soil moisture, which annual precipitation indirectly controls (McAndrews 1966).

As in the Holdridge experiments, the ecosystems suggested under doubled CO₂-climate lost forested land

Table 6.2
Primary Knowns, Uncertainties, and Unknowns Requiring Resolution in Order to Appraise
Forest Ecosystem Responses to Climate Change Induced by CO₂

Issues	Knowns	Uncertainties	Unknowns
<i>A. Issues Detailed in Other SOA Reports</i>			
<i>1. Carbon Cycle Issues</i>			
a. Atmospheric CO ₂ Accumulation	Atmospheric CO ₂ concentration is rising	Preindustrial CO ₂ value	Time when doubled and maximum CO ₂ will occur Maximum future CO ₂ concentration
	Seasonal CO ₂ amplitude is increasing	Source of increasing amplitude	Significance of amplitude changes to carbon cycle, vegetation, climate effects
	Land use (forest clearance) contributes to atmospheric CO ₂	Rates at which land-use generates atmospheric CO ₂ increases	Future contribution to CO ₂ by land use
b. Atmospheric CO ₂ Depletion	Oceans are the primary global atmospheric CO ₂ sink	Rates at which CO ₂ crosses the ocean-atmospheric interface by geographic region	Internal circulation of oceans by geography that controls up and down welling of CO ₂ -rich and CO ₂ -poor water masses
	Terrestrial biota is a secondary global atmospheric CO ₂ sink	Current areas and amounts of carbon stored in terrestrial biosphere	Future carbon source, sink, and storage properties of terrestrial biosphere
<i>2. Climate Effects Issues</i>			
a. Geography of Climate Change	Greater warming at poles than at equator	Intensity of latitudinal temperature differences	Local and regional temperature shifts
	Changes will occur in geography of precipitation	Geography of precipitation	Local and regional precipitation shifts
b. Variance from Mean Climate Changes	Variance may or may not change	Presence or absence of variance changes from current geography	Amount of variance change, if any, locally, regionally, globally
c. Temporal Chronology	Climate will change over time	Rate and nature (step function, climate continuous linear, etc.) of climate change	Temporal chronology of climate change
d. Seasonal Features of Climate Changes	Greater warming in winter than in summer	Amount of seasonal warming	Local and regional change in seasonal warming
	Quicker warming in summer than in winter	Time difference between summer and winter rates of warming	Local and regional time difference between summer and winter warming

Table 6.2 (continued)

Issues	Knowns	Uncertainties	Unknowns
3. <i>Vegetation Effects Issues</i>			
a. Applicability of Single Factor Greenhouse Experiments to Multifactor Field Situations	Published reports on single-factor experiments show increased photosynthesis, decreased water use, increased leaf area, increased dry weight, increased photosynthesis in shade	No published reports on multiple factor experiments that realistically simulate field conditions; whether mature trees and ecosystems will respond similarly	Amount, if any, of response in multifactor situations; quantitative importance of offsetting (canceling) factors to tree growth
b. Applicability of Short Duration (hour, day) Fumigations to Long-Term Tree Growth	Published reports on longer term (months, seasons) experiments show short-duration effects decline and/or disappear	Will field-grown trees cease responding to CO ₂ increases	How much, if at all, will field-grown trees acclimatize to enhanced CO ₂
c. Applicability of Experiments on Herbaceous Annuals, Leaves, Branches, and Tree Seedlings to Mature Trees	Effects in 3a are found in these plants or plant parts	Will mature trees respond as do plants or plant parts tested; if so, what is the nature of forcing function (linear, logarithmic, etc.)	Amount, if any, by tree species or by other functional unit (shade tolerance, growth rate, etc.) that trees will respond as do other plants or plant parts
d. Applicability of Experiments in 3a, 3b, 3c, to Regional or Global Vegetation	The few trees and fewer species examined to date have declined in growth, while CO ₂ has increased in concentration	Has the current 30% CO ₂ increase affected tree growth; importance of climate change and other pollutants during same period in depressing tree growth.	Will future changes in climate and atmospheric pollutants negatively affect tree growth; if so, how much compared with possible CO ₂ effects
B. <i>Issues Detailed in this Report</i>			
1. <i>Seedling Survival</i>	Temperature, precipitation variance control initial seedling survival CO₂ enhancement, below current forest floor concentrations, increases vigor, production, biomass, leaf area, and drought-tolerance differentially by species. Pathogens and predators destroy seeds and seedlings	Will temperature and precipitation variance change in the future Will CO₂ enhancement above current forest floor concentrations have the same effects Will pathogen and predator effects be different in the future	By how much, if any, will variance in temperature and precipitation change Will CO₂ increase have long-term effects on massive mortality and, if so, which species will be favored Which species will be favored and by how much if predator and pathogen effects occur

(continued)

Table 6.2 (continued)

Issues	Knowns	Uncertainties	Unknowns
2. <i>Sapling and Tree Growth</i>	Climate variance controls geographic ranges of mature species	Specific climate variables and their variance values controlling the cold, warm, and dry parts of each species' geographic range	Future local and regional climate variances; future effects of CO ₂ on responses of species to climate variance; future geographic range of species
	Climate variance controls annual growth rates	Specific climate variables and their variance values	Future local and regional climate variances; resultant shifts in competitive advantages among species
	Nutrients for growth depend on decomposition rates	Will decomposer populations change nutrients available because of warming of soils	Future amount of nutrients available because of changes in decomposer activities due to warming
	Root respiration depends on soil temperature, water, and oxygen availability	Will root respiration increase because of climate change	If root respiration changes, will it counteract increased production from CO ₂ if such increases occur
3. <i>Death and Reproduction</i>			
a. <i>Senescence</i>	Senescent trees die from stresses that younger trees can survive	If climate changes continuously, will trees become prematurely senescent because of the additional stress of this continuous change	Will CO ₂ induce vigor and prolong tree life and, if so, which species will be most affected and which will be least affected
b. <i>Catastrophic Age-Independent Mortality</i>	Wildfire frequency and intensity depends on climate, fuel, and time since last fire	Geographic change in wildfire frequency and intensity due to future climate change	Local, regional changes in the temperature and precipitation extremes that control fire frequency and intensity
	Windstorm and flood damage depends on frequency of rare climate extremes, topography, land-use	Geographic change in land use due to climate change	Local, regional distribution of future rare precipitation, wind extremes
	Pathogen, insect epidemics occur rarely	Climate dependency of pathogen, insect epidemics	Will climate control pathogen and insect epidemics and, if so, how

Table 6.2 (continued)

Issues	Knowns	Uncertainties	Unknowns
c. Chronic Age-Independent Mortality	Occurs when production is too slow to provide enough fixed carbon for metabolism, slowing growth, reducing resistance to stress	Quantification of "too slow" by species of tree	Will CO ₂ experiments with seedlings apply to mature trees, reducing chronic age-independent mortality; future local and regional distribution, frequency of climate variance that slows growth
	Chronic insect predation on trees is a normal stress that vigorous trees survive	Will chronic insect attacks change because of changing climate variance, changing forest composition	Climate variance that controls insect population sizes, species composition; forest composition that controls same
	Air pollutant damage (gaseous, acidic precipitation) is an increasing stress from which vigorous trees previously survived	Future air pollutant levels; loss of tree vigor by species to future air pollutant levels	Future combined effect of unknown air pollutant levels, climate extremes, insect, pathogen predation, and CO ₂ effects on forest growth
d. Plant Succession	Rates, outcomes of succession under current constraints by climate variance, seed sources, disturbance frequencies, CO ₂ concentrations	Will rates slow because of stress of possible continuous climate change; presence, intensity of forest-dieback and recovery	Will CO ₂ enhance rates by relieving stress; future local and regional distribution of climate constraints (variance); future disturbance by wind, fire, flood
e. Plant Migration	Trees migrated 100–400m/y in the past 10,000–15,000 years	Future migration rates on a land-use dissected landscape; survival of seedlings of species ill-adapted to new conditions	Availability of seed sources with time; availability of empty niches; tree planting

to nonforest vegetation in eastern North America and lost tundra and boreal forests to the north, clearly pinpointing that this phenomenon is an issue in the controversy over effects of rising concentrations of atmospheric CO₂. At the same time, southern mixed coniferous-deciduous forests and coastal plain forests (sources of much softwood lumber and pulp) expanded by over one-third. Although the estimated area of forests decreased in eastern North America, forest biomass and carbon storage increased as high carbon-density forests replaced those of low carbon-density (Solomon et al. 1984). At issue is whether the forest industry might benefit if this forest replacement occurred, and if so, how long such a replacement might take after the climate actually changed.

A serious limitation of both the climate and the ecosystem-based projection approaches is that each presumes that the same species growing together on today's landscape will, similarly, grow together, form the same plant communities, and compete with one another in the future. Periods with different climates than today's provide strong evidence to the contrary (see Davis 1983; Overpeck et al. 1985). A way to overcome this problem would be to circumscribe the geography of individual tree species with the geography of climate variables, as Bartlein et al. (in press) have done with pollen taxa and climate variables. Projections of future climatic regimes then would describe the geography of each species independently of the others. The drawback, of course, is that even more precise plant-geographic data are required by this approach than by the ecosystem projections described above. Solomon et al. (1984, pp. 18–21) describe their unsuccessful attempt to apply this idea to projecting future CO₂-induced climate effects on trees, based on tree inventory data collected routinely by the U.S. Forest Service.

In addition to the flaws in projecting static vegetation distributions that new research can correct, the empirical approaches are inherently incapable of characterizing the transient response patterns of forest ecosystems. The maximum life expectancy of most tree species is of the same order of magnitude as the expected appearance of doubled and quadrupled CO₂ concentrations (Perry 1982). Thus, the static forest ecosystems projected from empirical models will probably not be formed for many years after a climatic steady state is reached. The number of years involved and the nature of the transient forest ecosystems cannot be estimated simply with empirical projection techniques. Yet, the early (i.e., 100–200 years) transient responses are of most interest in any anthropocentric analysis of climate impacts.

To remedy this difficulty and to remedy the uncertainty of today's species associations continuing in the future, a different approach is required. This involves

modeling the processes that control vegetation dynamics, exemplified by the simulation model described next.

6.3.2 Simulation Projection Approaches

The issues emerging from exercises with simulation models of ecological patterns and processes are very different from those revealed after trials with the empirical models (See Section 6.3.3). A forest stand simulation model approach has been under development for the past 15 years (Botkin et al. 1970a, 1970b, 1972; Shugart and West 1977, 1980, 1981; Mielke et al. 1978; Tharp 1978; Doyle 1981; Weinstein et al. 1982; Shugart 1984). Adaptation of the model for assessment of forest issues in the global CO₂ problem has required a long but ultimately successful development period (Solomon et al. 1980, 1981, 1984; Solomon 1982, 1983a, 1983b in press; Solomon and Shugart 1984; Solomon and Tharp 1985; Solomon and Webb 1985; Solomon and West in press).

Conceptually, this simulation model is broadly analogous (although not in scale) to global climate models. The model essentially simulates the yearly growth of many individuals of different tree species on a single plot within a forest. Growth differs because of each species' characteristic maximum age and size; its tolerance to different amounts of shading, crowding, warmth, soil moisture; and so on. The model also simulates the annual variances in external climate variables and the effects of the variances on tree growth.

The concepts and biology incorporated in the model are described in detail by Shugart (1984) and Solomon et al. (1984). The mathematical expressions are provided by Shugart and West (1977) and Solomon and Shugart (1984). The approach implemented in projecting effects of future climate changes on forest dynamics uses the minimal information and mathematical relationships required to match the dynamic equilibrium found in forest stands. The model incorporates the complex ramifications of differing species responses to varying climatic factors in terms of the ecological and physiological processes of the forest system. Because the model contains the minimum amount of data and assumed processes needed to mimic natural forest dynamics, this approach can also reveal when there simply is too little information available to model a given phenomenon.

This model and several of its regional variants have been tested on vegetation at certain locations in the United States (east Tennessee, Shugart and West 1977; Arkansas, Mielke et al. 1978; Mississippi floodplains, Tharp 1978; Hubbard Brook, New Hampshire, Botkin et al. 1972, Aber et al. 1978, 1979, 1982, Aber and Melillo 1980, 1982; Puerto Rico, Doyle 1981) as well as

overseas (e.g., Australia, Shugart and Noble 1981). To supplement these studies of model validity in space, the model has also been tested with long temporal sequences of 10,000–20,000 years for which there are pollen records of actual forest composition (Solomon and Webb 1985).

The studies involving long temporal sequences, in particular, demonstrated that (1) the model results are consistent with long-term variations and processes in “real” forests (Solomon et al. 1980, 1981); (2) the model reproduces long temporal sequences and spatial patterns that are independently measured by pollen evidence (Solomon and Shugart 1984); and (3) the model reproduces the specific forest responses to unique climate configurations that occurred in the past, but do not occur today and are suggested by climate model simulations as results of future CO₂ increases (Solomon 1982; Solomon and Shugart 1984; Solomon et al. 1984; Solomon and Tharp 1985).

This approach has certain advantages over the empirical ones. Transient vegetation responses to environmental changes can be simulated because a dynamic rather than a static system is modeled. Effects also can be modeled of future climate variable combinations that have no modern analogs. The model allows the recombination of all tree species that possess overlapping affinities to climate variables, rather than being limited to the set of vegetation communities and climate variable combinations on the modern landscape.

The capabilities and validity of these approaches in matching vegetation on the modern landscape are illustrated in Figure 6.2. The forest types of eastern North America are mapped in Figure 6.2A (Braun 1950; Rowe 1977). Simulations of present vegetation correctly reproduced these forest types in terms of forest structure (size and percentage composition of trees) and of dominant, subdominant, rare, and excluded species at each site (Solomon et al. 1984).

Figure 6.2B shows forest zones mapped by the Holdridge system in which no attempt was made to fit Holdridge classes to known vegetation geography (Emanuel et al. 1985). The geographic pattern of forest types was generally reproduced. Although vegetation-type boundaries are not accurate, certain subdivisions are unrecognized by ecologists at this spatial scale (e.g., moist and wet boreal forest), and other subdivisions, normally recognized, are missing (oak-hickory-pine ecosystem).

The use of climate variables explicitly selected to circumscribe forest-type boundaries is illustrated in Figure 6.2C (Solomon et al. 1984). As one would expect, the similarity of Figure 6.2C with recognized forest zones in Figure 6.2A is considerably better than that shown by the Holdridge system in Figure 6.2B, particularly in correcting the spurious and missing zones of the Holdridge system.

Although the simulation approach (Figure 6.2A) is obviously more accurate than the two empirical estimates (Figure 6.2B, 6.2C), it has certain disadvantages over the empirical methods. The simulations require much more information on plant biology and natural history characteristics of species than is easily obtainable and, frequently, than is known in some areas of the Earth. If the data were available, simulations covering the large areas that Emanuel et al. (1985) treat would be prohibitively expensive in manpower and dollars. Even if the simulations could be run, they would only cover forested landscapes. Available simulation models essentially generate quite reliable projections of present vegetation at the expense of comprehensiveness; whereas the opposite is true of the empirical approaches.

Despite being the most detailed and accurate of the model approaches available, the simulations still do not mimic the forest system adequately. The model used to simulate effects of CO₂-induced climate changes (Solomon et al. 1984; Solomon in press; Solomon and West in press) does not consider certain processes that are likely to be important under such climate changes, for example, the incorporation of localized soil nutrients and turnover. The likely result of excluding nutrient cycling from the CO₂-climate simulations would be greater simulated community productivity than would actually occur if nutrients limited growth of species on present and future landscapes.

Other processes not modeled include the interacting effects of chronic diseases and atmospheric pollutants. Insects, disease, and their vectors (such as other insects, fungi, and bacteria) have their own, often complicated, life cycles, which depend on weather and climatic events in a manner different than the life cycles of the host trees. No model has yet been applied to the complex ramifications of pathogen, insect, and tree life cycle interactions under CO₂-induced climate change and other environmental perturbations. A large-scale regional research program at several cooperating institutions is under way to determine the chronic effects of acidic precipitation on forests, based on field studies and the forest-stand model (e.g., see McLaughlin et al. 1983a, 1983b). This effort might be extended to include insects, pathogens, and other air pollutants, as well as climate change.

The direct effects of atmospheric CO₂ on forest growth and development have also not been modeled here or elsewhere (Strain and Cure 1985). West and Solomon (1984) used the little relevant data available to incorporate carbon fertilization effects into simulated forest species to model combined direct and climatic effects. They surmised that, if the assumptions required to model direct effects prove correct, the indirect effects of climate change and land uses are likely to be much more apparent in forest behavior than will the carbon

fertilization effects, a presumption recently suggested from other analyses (Strain 1985, p. 228). Both West and Solomon (1984) and Strain (1985) concluded that too little data are available on which to base models and expectations of future ecosystem carbon dynamics.

Finally, the model itself is inherently limited by the presence of mountains, oceans, and other nonclimatic restrictions to the geographic ranges of tree species. Within the present form of the model, such boundaries must be assumed to coincide with climatic barriers, although this is clearly not the case for some species.

6.3.3 Issues Described by Model Exercises

The results of model exercises and experiments illustrate a potential forest ecosystem response ranging from insignificant to drastic. Additional research is required to accurately project forest responses to CO₂-induced climate changes. Despite their inadequacies and disadvantages, the model experiments by Solomon et al. (1984), Emanuel et al. (1985), and Solomon and West (in press) are realistic enough to demonstrate several

issues, particularly those that follow from the potentially great changes in forest distribution, composition, and structure if CO₂ concentration and climate shift as projected. These issues, in turn, determine the research needed to resolve uncertainties involving forest response to changing climate. For discussion, the issues and research needs can be subdivided into (1) the indirect effects of immediate concern; and (2) the direct effects, that is, vegetation response, climatic effects, and carbon-cycle phenomena (MacCracken and Luther 1985; Strain and Cure 1985; Trabalka 1985).

6.3.3.1 Indirect Effects

Knowledge of tree and forest response to climate change is based almost entirely on transient-free measurements. Yet, the multicentennial time spans required for tree maturity indicate strong likelihood of lags in forest response to rapid climate change. On the other hand, most research objectives of direct interest to society concern events that may occur within the next few decades. Most predictive capabilities presently include

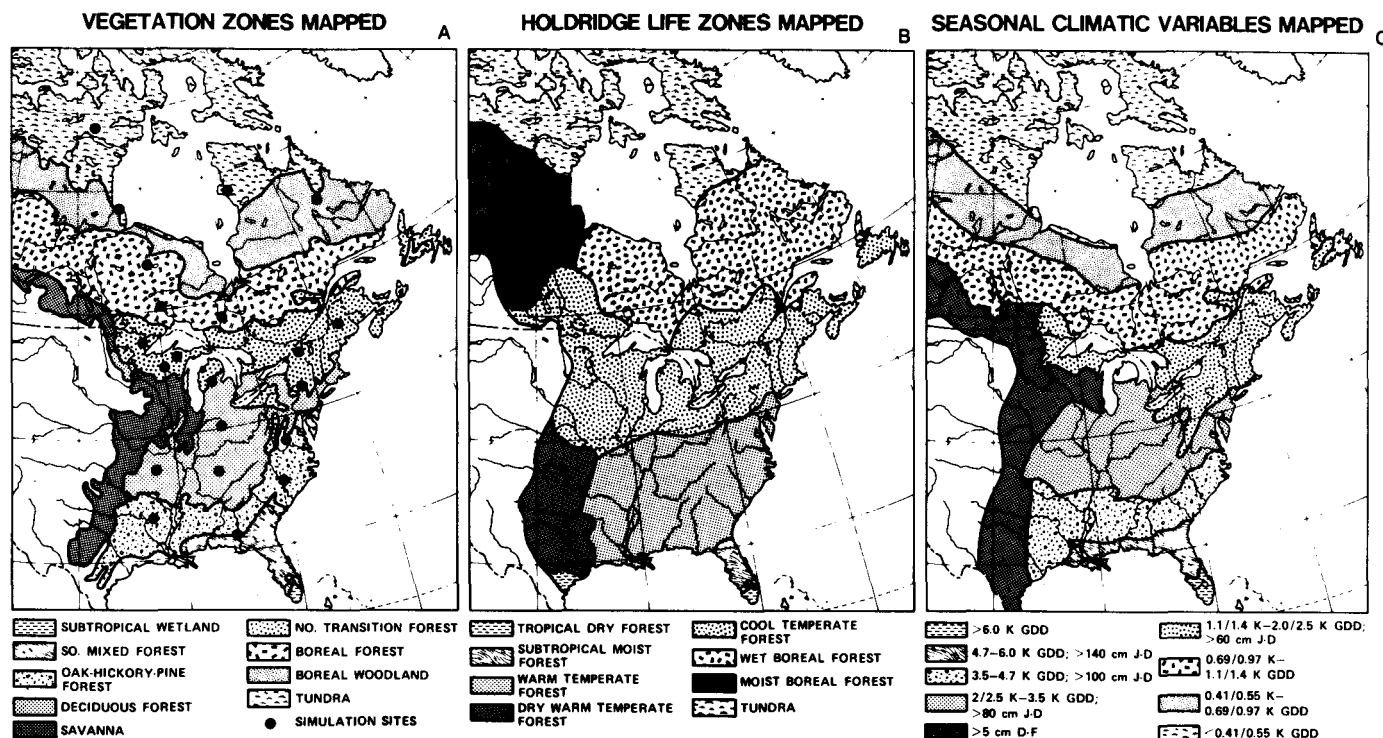


Figure 6.2. Different approaches to the problem of reproducing the present vegetation of eastern North America. (A) Present vegetation zones (Braun 1950; Rowe 1977, including locations (black circles) where forest-stand simulations generated the correct vegetation (see Solomon et al. 1984 for details); (B) Vegetation zones defined by climate variables in the Holdridge life zones classification system (redrawn from Emanuel et al. 1985); (C) Vegetation zones defined by specified isotherms of growing season heat sums and annual or winter precipitation (J-D is January-December; D-F is December-February; CM is centimeters of precipitation; GDD is growing degree days, and K is thousand (see Solomon et al. 1984 for details).

only static, landscape-level vegetation configurations some unknown hundreds of years in the future. Clearly, there is a critical need for more research on approaches that model both decadal and millennial transient responses of vegetation and for the specific field data required to support, extend, and improve such models. For example, the answers to many questions on long-term growth and dynamics of forests are to be found in applying simulation models to the increasingly well-documented paleoenvironmental records of the past 10,000 years (Solomon and Shugart 1984; Solomon and Tharp 1985; Solomon and Webb 1985; Webb 1985).

Generally, all model approaches suggest that climate change would induce great changes in the distributions of ecosystems and their characteristic species. In response to such stress, mature trees can die in a year or two, whereas their seedlings require tens to hundreds of years to reach maturity. Therefore, the shifting geographic distribution of trees in response to a CO₂-induced climate change could result in a period with few mature trees and forests. This "dieback period" could be further lengthened if future responses of trees resemble those projected in the simulations of warming effects (Solomon et al. 1984; Solomon and West in press). In these simulations, most deciduous species grew throughout current deciduous forest regions of the Eastern United States more slowly than they do today. This hypothetical growth reduction appears similar to that recently documented by McLaughlin et al. (1983b). An obvious issue, thus, is the need to identify the environmental force(s) causing the present diebacks in forests.

The initial warming caused by increasing concentrations of atmospheric CO₂ produced a simulated dieback of many dominant tree species (Solomon et al. 1984). At the boreal-deciduous forest transition, the dieback was similar in appearance to the results of epidemic pathogen attacks. Farther north in boreal forests, deciduous tree species eventually replaced the present-day southern boreal forests, but not before boreal species virtually disappeared; therefore, an important issue for research is the possibility that the northern softwoods, which constitute most of the world's supply, might be very rare throughout the globe for several decades or even hundreds of years.

All the projections indicated extinction of boreal trees and their replacement by deciduous species. Such a changeover could be time-transgressive; that is, it first occurred in simulations in the south and later in the north, independent of any migrational lags (not simulated). Some of the intrinsic, time-transgressive lags could extend up to 300 years after the climate change ceases (Solomon et al. 1984, p. 75), a property of transient forest response similar in

time scale to that expected from ocean temperature change (e.g., see Schneider and Thompson 1981). Only the least compositionally complex forests (northern boreal forests, arid western woodland) might behave as one would expect without using a stand-simulation model. Boreal forests could invade present tundra, closed forests could replace open northern boreal woodlands, and dying trees may not be replaced by any tree species in dry western woodlands because prairie grasses could dominate there. Experiments based on the Holdridge approach yielded similar responses in these areas (Emanuel et al. 1985).

6.3.3.2 *Vegetation Response*

Perhaps the most important limitation to using the models as proxies for the future effects of climate change is the lack of knowledge required to simulate the hypothesized enhanced growth due to increased concentrations of CO₂ in the atmosphere, that is, the CO₂ fertilization effect (Kramer 1981). Only new, long-term (decadal) field and greenhouse experiments can address the direct effects of CO₂ on tree growth (see Strain and Cure 1985) and the subsequent shifts in response by trees to climate. There is, presently, a critical need for direct scientific evidence to support the suggestion that decade- or century-old trees will behave the same as annual crop plants, leaves of trees, or seedlings used in published short-term (hours, days) greenhouse experiments. There is a critical need for scientific evidence to support the suggested application of results from single-variable experiments to the real world of multiple, interacting environmental and biotic variables.

The issue for indirect effects research is how such effects might change the ways in which individual species respond to climate, for example, by increasing each species' photosynthetic temperature optimum, by decreasing their drought sensitivity, by delaying senescence, and so on. LaMarche et al. (1984) suggest that the measured tree growth of the past 100 years at very high altitudes matches expected growth should increased atmospheric CO₂ concentrations enhance tree growth. The important issue for indirect effects research is that these trees appear to respond to temperature differently now than they did before about 1850.

The reduction in tree growth below 11,000 m altitude elsewhere (e.g., McLaughlin et al. 1983b; Johnson 1983; Plochmann 1984), if attributable to other atmospheric contaminants (gaseous air pollutants, acidic precipitation, and so on), produces similar uncertainties; that is, trees may be responding to climate differently under its current influence than they did when present tree ranges and densities were determined tens and hundreds of years ago. If tree

response to simultaneous changes in climate, CO₂, and pollutants is to be estimated, the obvious research needs involve documenting how tree species responded to climate (1) in the absence of changes in these other environmental variables (e.g., immediately before the industrial revolution) and (2) in the absence of changing pollutants but during shifts in atmospheric CO₂ (e.g., at the end of the last continental glaciation).

Certain versions of the forest-stand simulation model have incorporated concepts (Botkin et al. 1973; Shugart et al. 1984) and the few available data (West and Solomon 1984) on effects of CO₂ fertilization. Model experiments indicate that the primary impacts could involve accelerated growth, increased age, and reduced impacts of the environmental changes simulated without CO₂ fertilization (e.g., forest dieback and recovery, invasion of boreal forests by deciduous species, and so on; West and Solomon 1984). Even with unrealistically high growth enhancement (Shugart et al. 1984), hypothetical tree growth and forest community productivity did not exceed about 15–20% of current values, which would be far too little to outweigh the considerably larger growth losses simulated in the absence of direct vegetation effects (Solomon et al. 1984; Solomon and West in press; Solomon in press).

More data on responses of mature trees and on responses of many tree species to increased atmospheric CO₂ concentrations are required to characterize potential CO₂ fertilization and increased water-use efficiency. If CO₂ fertilization does occur in unmanaged forests, it will then clearly benefit some species more than others. Evidence identifying the species that will advance or decline and quantifying the response is needed. Indeed, there is a critical need for evidence that any tree life stage beyond that of seedlings will benefit from CO₂ fertilization. Thus, data on the presence of CO₂ fertilization and water-use efficiency phenomena must be obtained from trees growing in unmanaged stands in order to hypothesize and then accurately simulate the effects of carbon fertilization in forests.

6.3.3.3 *Climatic Effects*

The implications of the ecosystem modeling exercises to climate modeling may not seem particularly significant, except perhaps in defining forest and nonforest areas for use in albedo estimates (Emanuel et al. 1985) or in estimating CO₂ source and sink properties of forests, discussed below (Solomon et al. 1984). On the other hand, the foregoing illustrates the crucial importance in indirect effects assessment of improved, expanded, and more valid estimates of regional climate variables under changes induced by atmospheric CO₂.

Improvements in GCMs of the atmosphere are critical to understanding the improvements that will

be effective in assessing responses by biotic systems. Climate uncertainties are at least an order of magnitude more important than biotic uncertainties (1) because of uncertainty amplification when errors are propagated through successively later steps of the forcing and response systems, and (2) because of the deficiencies of GCMs for this purpose. The most immediate needs for a valid assessment of forest response to CO₂-induced climate change include information in the following four areas.

First, reliable GCM simulations of CO₂-induced precipitation changes are required. Dense tropical forests presently grow in coastal Venezuela, whereas sparse desert shrublands grow on the nearby island of Aruba, which has similar temperatures, but less precipitation. Tropical forests modeled by Emanuel et al. (1985) increase in areal cover by 15% if only warming induced by doubled CO₂ is considered. The precipitation regime in most regions can produce treeless grasslands; open, slow-growing forests; or dense, rapidly expanding ones, all under the same temperature regime. Clearly, precipitation changes will be at least as important to forests as temperature changes. Reliable precipitation estimates are required to determine whether a given forest will be a net source or a net sink for carbon.

Second, GCM projections of CO₂-induced climate change are at such a coarse spatial scale that only the most general features of vegetation response can be examined. The entire boreal forest of North America is restricted to a latitude band of a few degrees. Mean July temperature at the southern boundary is only 2°C warmer than at the northern boundary. Climate that controls the southern boundary (ca. 0.5° latitude band) is different from that which controls the northern boundary. General circulation model simulations at 2°–10° latitude and longitude resolution do not apply to the dynamics of even such general features of vegetation as the boreal forest geography.

Third, GCM projections of climate variance are required, that is, numerical estimates of the oft-suggested view that variance is greater with cooling and less with warming (e.g., Wigley and Jones 1981; Palutikof et al. 1984). The empirical projections of Emanuel et al. (1985) and Solomon et al. (1984) assumed that climatic mean values define vegetation types. With the coarse spatial resolution used, this may be a reasonable approximation. The experiments of Solomon et al. (1984) and Solomon and West (in press), to simulate more realistic vegetation dynamics and thus to define issues more precisely, used climate variance but assumed that variance remains constant. This is clearly both an unwarranted and an important assumption: climate variances, not mean values, control vegetation response in reality and in the simulation models.

Fourth, the likely rate at which climate may change (i.e., the rate at which atmospheric CO₂ concentrations will increase) must be known. Simulations indicate that forest growth may be more sensitive to the rate at which climate warms than to the magnitude of warming. Rapid warming could increase tree mortality rates, both directly and through enhanced susceptibility to stress, while simultaneously, it slows the rate at which trees grow to maturity. On the other hand, a very slow rate of climate change may approach, in order of magnitude, the rates of tree replacement. In this case, tree growth lags would have an insignificant effect on overall forest stability.

6.3.3.4 Carbon Cycle Dynamics

The rate at which climate will change depends directly on the rate at which CO₂ will accumulate in the atmosphere and the rate at which it will be removed to oceans and the terrestrial biota. These present and future fluxes must be defined. The roles of oceans and the terrestrial biota

in regulating the global carbon cycle require much better definition than is presently available. The rates at which human populations release carbon to the atmosphere, through deforestation and fossil fuel use, are central to determining the rates of atmospheric CO₂ increases alone and to projecting the resultant climate change rates. These rates of climate change, in turn, are as important as the magnitude of climate change in forcing a forest response.

The model work to date contains certain implications for the role of forests as sources or sinks of CO₂ in the global carbon cycle. Model experiments by Emanuel et al. (1985) hypothesize little difference in global terrestrial carbon storage between present and doubled CO₂ temperatures. Simulation modeling of a much smaller area (Solomon et al. 1984) indicates a similar result, with important exceptions because of the transient effects of forest response to slowly changing climate. This issue is addressed in Figure 6.3, which presents aboveground carbon storage differences

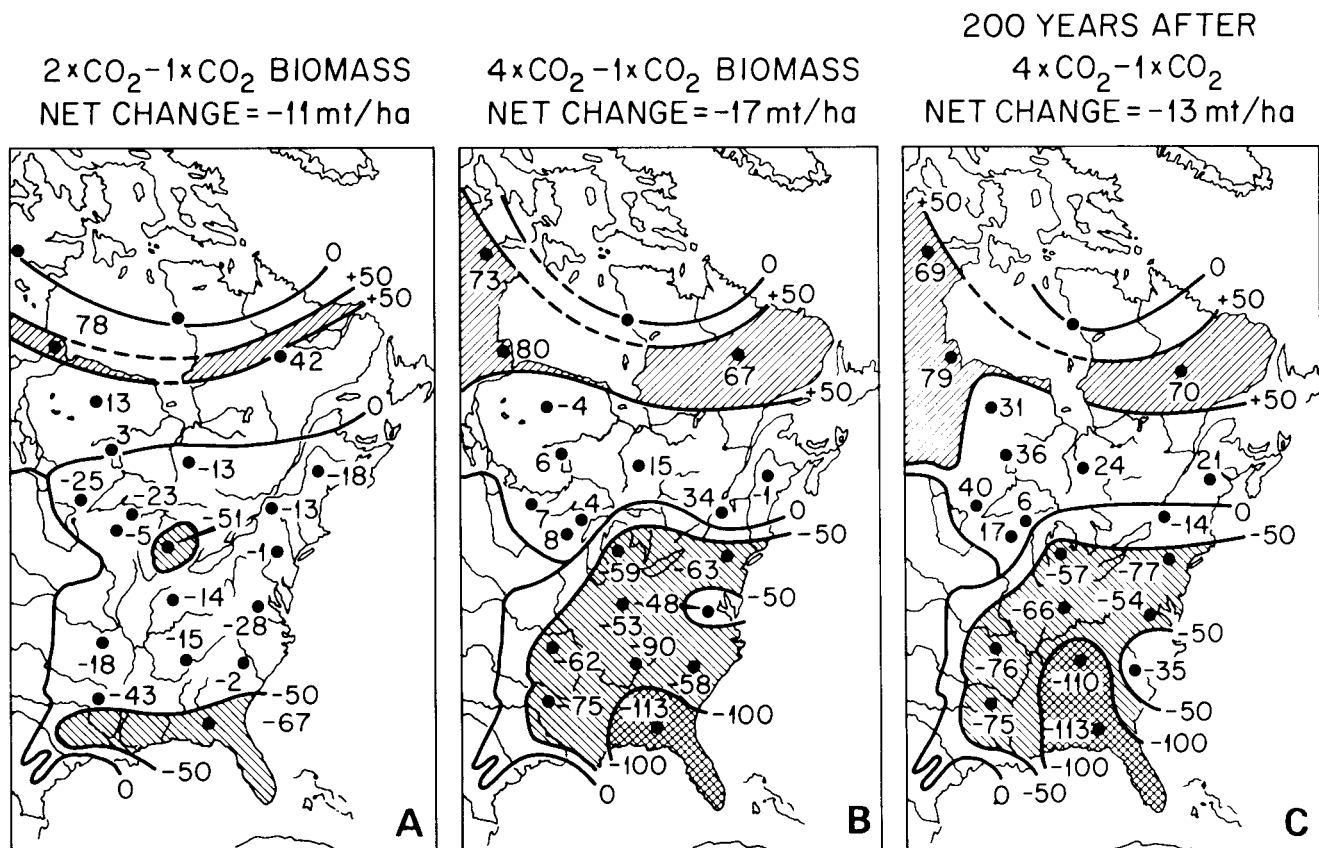


Figure 6.3. Carbon storage dynamics (in metric tons per hectare [mt/ha]) simulated at 21 sites in eastern North America. Maps show differences between carbon storage simulated with contemporary climate and that simulated with 2 × CO₂ climate (A), 4 × CO₂ climate (B), and 200 years after 4 × CO₂ climate stabilizes (C) (Solomon in press).

between the pre-CO₂-induced warming (300 years into simulations) and that which occurs at the time of CO₂ doubling, at the time of CO₂ quadrupling, and at 200 years following stabilization of CO₂-induced climate change (i.e., 900 years into the simulations). Values on the maps at each of the 21 sites simulated represent the hypothetical gain or loss of live, aboveground stand biomass in megagrams per hectare.

By the time simulated doubling of CO₂ occurred (Figure 6.3A), the aboveground biomass at the sites simulated in the northern portion of the subcontinent became a carbon sink, and at sites in the southern portion, the aboveground biomass became a carbon source, with carbon balance achieved at about 50° north latitude. The present forest-prairie border implies a western limit to carbon losses and implies gains in closed-canopy forests, both of which are repeated in empirical modeling experiments (Emanuel et al. 1985). This model result emphasizes the presently unanswerable question of how important carbon storage dynamics might be as a function of different ecosystems at different latitudes.

The strongest aboveground carbon sinks at the 2 × CO₂ point in the simulations (Figure 6.3A) were simulated along the northern boreal forest border where, hypothetically, the forest invaded tundra. The greatest carbon sources were simulated in the Southern United States where forests are currently under moisture and temperature stress. As a group, the sites were simulated to be carbon sources, losing 10% of the live biomass stored prior to CO₂-induced changes in climate. By the time modeled CO₂ quadrupled (Figure 6.3B), total simulated carbon storage declined an additional average of 5% per site. The strong northern carbon sinks and southern carbon sources intensified and increased in areal cover. Meanwhile, the carbon-balance line migrated southward by 5° latitude (550 km); that is, carbon sinks were growing more rapidly in northern areas than they were shrinking in the southern areas. These results suggest needed research that concentrates on forests of the Southeast United States and in boreal regions of Alaska and Canada.

Some 200 years after climate change ceased at the 4 × CO₂ level (Figure 6.3C), hypothetical carbon storage dynamics continued. Carbon sources intensified in the southeast, and the high-density northern carbon sinks expanded southwestward. Although the carbon-balance line appears to have undergone little geographic change, hypothetical carbon storage increased an average of 3% across the 21 sites during the 200-year period following stabilization of climate. The continuation of obvious changes in modeled carbon storage dynamics long after climate stabilization is a property of the global carbon cycle previously considered mainly in relation to soil organic matter pools and to

the atmosphere-ocean interface. Thus, response lags of many decades in terrestrial biotic carbon storage may be legitimate carbon cycle issues. They may require numerical characterization if changing atmospheric CO₂ and climate are to be accurately modeled.

6.4 SUMMARY

The foregoing report reviews the characteristics of forest trees and the issues created by climate changing in response to rising concentrations of atmospheric CO₂. Among the many issues, problems, and research needs discussed (Table 6.3), the following five are the most important:

1. Compared to those of agricultural crops and commercial fish species, the life spans of trees are long enough to create unique requirements for climate and vegetation data needed in understanding tree dynamics.
2. Despite management practices, forests are ultimately dominated by climate stability and change. Therefore, climate control of forests must be understood if forest management is to use or ameliorate climate change effects.
3. The direct effects of increased atmospheric CO₂ concentrations on forests could range from a pronounced growth enhancement to negative effects on tree growth.
4. The direct CO₂ effects, combined with effects of changes in climate, air pollutants, and other environmental forces could result in forest responses ranging from enhanced growth to tree die-off. To date, only the latter outcome in forests has been reported in scientific literature.
5. There are essentially two kinds of models used in documenting the issues and defining the research needed to resolve these issues. Models based on empirically derived relationships are comparatively easy to parameterize and are particularly useful for defining problems visible at broad scales of space and time. Models based on the processes that determine tree and forest responses to environmental forces are more difficult to parameterize but are effective in defining problems that are too complex or at too fine a scale to be treated by empirical models.

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Table 6.3
Variables, Data, and Ecological Responses that Must be Documented
to Project Effects of CO₂-Induced Climate Change on Forests

Environmental Variables	Affected Organisms, Life-Stages, or Environmental Variables	Primary Responses	Secondary Responses
Climate Variables			
Temperature Variables			
Frequency, Intensity of Winter Low Temperatures	Saplings Trees	± Death of saplings ± Loss of buds, branches	Loss of reproduction, tree damage
Frequency, Intensity of Spring Frosts	Spring-germinating seeds Trees	± Death, by species ± Defoliation	± Growth of tree, by species; mortality
Cumulative Growing Season Warmth	Saplings, trees Soil biota	± Growth of tree, by species ± Nutrient release rates	± Increased disease ^a mortality, ± Growth of tree, by species
Frequency, Intensity, Length of Heat Waves in Midsummer	Seedlings Fire frequency	± Death, by species ± Death, damage, by species	± Increased disease ^a mortality
Frequency, Intensity of Fall Frosts	Fall-germinating seeds	± Death, by species	
Precipitation Variables			
Frequency, Length of Flooding	Seedlings Saplings, trees	± Death ± Death, slowed growth, by species	± Increased disease ^a death by species
Frequency of Spring Soaking Rains	Seedlings	± Death from soil biota, by species	
Growing Season Precipitation as Soil Moisture	Seedlings Saplings, trees Soil biota	± Death if too little/too much, by species ± Growth of tree, by species ± Nutrient release rates	 ± Increased disease ^a death by species ± Growth of trees, by species
Frequency, Intensity of Growing Season Droughts	Seedlings Mature Trees Fire frequency	± Death, by species ± Slowed, stopped growth, by species ± Death, damage; reproduction by life stage and species	 ± Increased disease, ^a death by species
Intensive Wind Storms, Ice Storms	All trees, largest trees, shallow-rooted trees	± Death, damage; enhanced reproduction by species	± Increased disease, ^a mortality
Human Variables			
Land Use	All trees	Homogeneous age structure of stands	Increased disease ^a stress changes to the stand level
CO ₂ Concentration	Seedlings No other tree life stages measured	Increased growth and carbon storage, enhanced drought-tolerance Unknown	Increased seedling survival; other responses in other life stages possible
Acidic Precipitation	Seedlings, saplings, trees	± Growth of tree by species ± Nutrient release rates	± Increased disease, ^a mortality ± Growth of tree, by species
Gaseous Pollutants	Seedlings, saplings, trees	± Growth of tree by species	± Increased disease, ^a mortality

^aDisease denotes changes in tree growth due to some combination of changes in frequency or intensity of attacks by bacteria, fungi, and/or insect populations.

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7. HUMAN HEALTH: ANALYSIS OF CLIMATE RELATED TO HEALTH

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7.1 INTRODUCTION

This chapter is to determine the information and data needed to study future impacts of elevated carbon dioxide (CO₂) on human health. An increase in atmospheric CO₂ is predicted to have several direct or indirect effects on human health, including climate change, changes in vegetation (due to changes in fertilization and water-use efficiency of plants), changes in ocean chemistry (due to increases in dissolved CO₂), and possibly slight changes in human biochemistry and physiology (due to breathing air with elevated concentrations of CO₂).

Changes in vegetation may affect water availability for agriculture and human use, human nutrition, materials for shelter, and so forth by affecting water resources, agriculture, and forests. Chapter 2 of this volume briefly describes the expected vegetation effects, and the *Direct Effects of Increasing Carbon Dioxide on Vegetation* (Strain and Cure 1985) has more detail regarding current knowledge in this field. The chapters on water resources, agriculture, and forest (3, 4, and 6 of this volume, respectively) point out how changes in vegetation may affect these issues.

Changes in ocean chemistry may affect fisheries that in turn may affect nutrition, especially in some of the developing regions of the world. Information on the carbon cycle is described briefly by Blasing in Chapter 2 of this volume. More detail will be found in *Atmospheric Carbon Dioxide and the Global Carbon Cycle* (Trabalka 1985). Potential effects on fisheries are described briefly in Chapter 5 of this volume.

It has been suggested that breathing elevated concentrations of CO₂ may change human physiology and biochemistry even though if the atmospheric CO₂ concentration were quadrupled (to approximately 1200 parts per million [ppm]), it would still be only about 1/40th of the concentration of CO₂ in the air expired from the lungs (approximately 5% or 50,000 ppm). Humans have been exposed to much higher concentrations of CO₂ than those expected in the atmosphere with no persistent deleterious effects. However, these exposures were intermittent or were for periods of 6 months or less. Two reviews of this literature (Bland et al. 1982; U.S. Department of Energy [U.S. DOE] 1982) indicate that, if there is an effect in breathing very low but elevated concentrations of CO₂ over prolonged periods, it is probably extremely small. In addition, the exposure limit to CO₂ concentration recommended by the National Institute of Occupational Safety and Health (NIOSH) is 10,000 ppm for up to 10 h/d (U.S. Department of Health and Human Services 1985). Thus, this possible effect of elevated CO₂ will not be discussed further in this document although eventually long-term, low-

level laboratory studies may be needed to determine whether there is an effect.

This chapter, therefore, concentrates on the effects of climate change on humans. Climate and particularly weather elements influence human health because some diseases are quite prevalent in some climates but are either less prevalent or absent in others. Increased atmospheric CO₂ is expected to raise the average global temperature by about 1.5°–4.5°C (MacCracken and Luther 1985a, 1985b). In temperate zones this increase is expected to be about equivalent to the global average, whereas increases in tropical zones are expected to be smaller and increases in the polar areas are expected to be greater. Thus, the boundaries of the tropics may extend into the present semitropical regions, part of the current temperate zones may become semitropical, and so on. There are, as yet, no firm predictions regarding seasonal temperature changes in specific regions or regarding changes in other meteorological variables such as humidity and precipitation. In addition, it is not known whether the variability of climate or weather will change, that is, whether there will be fewer or more periods of heavy or light precipitation, fewer or more excessively hot periods, and so on. Because of these uncertainties, it is currently impossible to predict the impacts of CO₂-induced climate change on human health; we can only point to some of the known influences of climate, seasons, and weather on human health and specify the data and information needed, both from the CO₂ research program and from human health research, to eventually assess the effects of CO₂-induced climate change on human health.

It must be emphasized that nonmeteorological factors currently do, and in the future will, modify the effects of meteorological variables on health. Humans currently live in extremely cold and extremely hot climates and survive by modifying their ways of life (clothing, shelter, food, etc.). They will, of course, probably continue to do so under a CO₂-induced climate change. In addition to these behavioral adaptations, there are passive mechanisms in the human body, collectively termed the thermoregulatory system, which enable humans to adjust to some extent to adverse meteorological conditions.

Furthermore, although climate provides the underlying environment that determines the potential for the prevalence of some diseases in specific climates, human circumstances, attitudes, and interventions (or lack thereof) can, in many cases, modify the prevalence of these diseases. For example, the socioeconomic status of regions and individuals, cultural practices, quality of health care and education, effort and funds expended for eradicating disease-causing organisms have a major influence on the prevalence of some diseases. Thus,

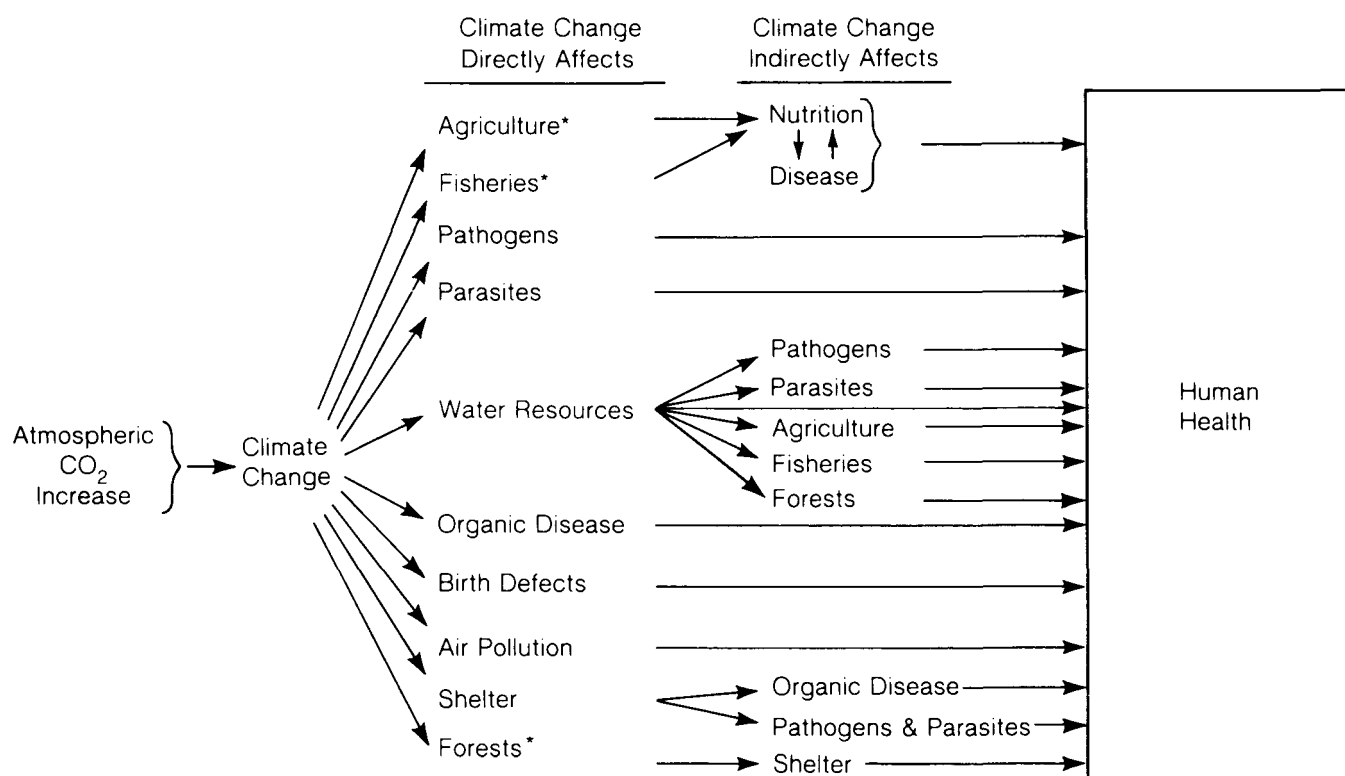
although we can identify (but not always quantify) influences of meteorological variables on human disease, in many cases the end result of climate change on human health will be modified by many other factors.

Pertinent information in the literature is limited in several ways. First, it would be desirable, for purposes of this study, to know how much climate and weather variables influence the onset and progression of organic diseases. However, mortality (death) statistics are much more readily available than are morbidity (illness) statistics, with the exception of some communicable and parasitic diseases that are required to be reported to public health authorities. Therefore, most studies designed to measure the health of populations use mortality statistics. These studies state cause of death and where and when the person died; thus, these data can be matched with environmental conditions of the time, and inferences can be made on whether these conditions influence the death rate from particular diseases. These mortality statistics do not tell us when the disease, which eventually killed these people, originated or what the environmental conditions were at that time. There is little knowledge regarding whether climate or the prevailing weather conditions are synergistic with other factors in instigating or in determining the rate of progression of some diseases.

Second, in some cases, the literature referred to in this report is relatively old. This is a consequence of the fluctuations of interest in and funding for different areas of research. In particular fields, little research has been done in recent years; however, much of the older literature is creditable research and relevant to this study. In addition, there are many other studies that would reinforce the literature quoted that have not been included for the sake of conciseness.

Third, until the CO₂ issue arose, there was no particular reason to study the effects that regional climate change might have on human health because climate change was not expected to occur, except possibly extremely slowly, over hundreds of years. Therefore, most studies investigated the effects of large variations in weather (heat waves, cold spells, etc.) but did not look for possible effects of persistent climate change in a region.

This chapter will describe some of the ways that climate and weather influence human health, some of the modifying factors, and the information and data needed to initiate assessment of the possible impacts of elevated atmospheric CO₂ on human health. Figure 7.1 indicates pathways by which climate change may modify human health.



*Agriculture and forests may also be directly affected by an increase in the concentration of atmospheric CO₂. Fisheries may be affected by CO₂-induced changes in ocean chemistry.

Figure 7.1. Pathways by which CO₂-induced climate change may affect human health.

7.2 CLIMATE AND WEATHER

7.2.1 Weather Variables Relevant to Human Health

All climate and weather variables have some influence on human health. The effect may be either directly on the human body or indirectly through effects on disease-causing organisms or their vectors. Although the effects of variation of only one weather element may be examined in a particular study, that element does not act independently of other elements, for example, changes in humidity modify the effects of temperature.

Extreme temperatures endanger human health. The acute effects of excessive cold are frostbite and, for prolonged exposure, death from lowered body temperature. The acute effects of excessive heat, such as heat stroke and heat edema, if not treated quickly, can cause death. People with chronic diseases, especially the elderly, are very susceptible to aggravation of the disease state from both excessively cold and excessively hot weather. Temperatures in tropical, subtropical, and warmer temperate zones are ideal for the survival and propagation of causative agents for some bacterial, viral, and parasitic diseases. Temperature also affects human health by affecting agriculture, fisheries, and water resources.

The effects of high temperatures on human health are modified by the amount of moisture in the air (humidity). The degree to which thermoregulatory mechanisms must operate to keep body temperatures normal varies with humidity. Human comfort is also affected by humidity. Certain levels of humidity are ideally suited to the survival and reproduction of pathogenic bacteria, viruses, parasites, and their vectors.

Precipitation may increase humidity with consequent effects on humans. In cold weather, it may add to chilling of the human body, thus making the human more susceptible to disease, or it may aggravate chronic diseases. Depending on the amount and timing, it may modify the ecological habitat of parasites, their hosts, and insect vectors such that their growth and survival are affected. If there is too little or too much precipitation or the timing is wrong, there may be crop damage. This may lead to food shortages or an increase in the cost of food, thus resulting in under- or malnutrition.

Abrupt changes in weather, such as those associated with the passage of a weather front, have been implicated in such things as feelings of discomfort with symptoms such as headaches. There is some evidence that weather changes may be related to the onset of some diseases, such as common colds.

Wind in combination with temperature and humidity can affect human thermoregulation. It can also be a means of spreading the causative agents of disease, insect vectors, and allergens.

7.2.2 Effects of Slow Versus Fast Climate Change

The rate of climate change will be a major factor in the intensity of the effects and the efficiency of adaptive (passive) responses and ameliorative actions. Physiological changes begin within minutes of an abrupt change in temperature, but it takes time to become completely acclimated to a change. For example, changes in types of clothing can be a rapid response to climate stress; however, architectural changes in housing, particularly in existing structures, take long periods of time. New strains of plants can be developed that will tolerate a new climate, but this development may take a number of years. New water storage facilities take a number of years to plan and build. Thus, if there are appreciable and rapid changes in climate, adaptation will be difficult. If there is gradual change, over 25–50 years, many changes can occur, either passively or actively, to offset possible detrimental effects.

7.2.3 Changes in the Variability of Weather

Climate changes may either increase or decrease the variability of weather; that is, there may be fewer or more heat waves, excessively cold spells, excessively heavy rains, and cold or warm fronts. These changes from normal weather may be either beneficial or detrimental to human health. The extent and direction of changes in variability under a CO₂-induced climate change currently are not known, but this information will be very important in determining the effects of climate change on human health.

7.3 BASIC MECHANISMS IN HUMANS

7.3.1 Thermoregulation, Acclimation, and Adaptation

With climate change the microenvironment, particularly the temperature in which humans live, will change. The human body has a certain amount of physiological adaptability to the environment. There are passive mechanisms that are triggered more or less continuously by changes in body temperature. For the human body to function properly, the core (internal) body temperature must be kept in a constant range (about 37°–37.5°C). These mechanisms react to changes in the surface body temperature. The surface temperature of the body changes, for example, as ambient temperature changes, or changes as we move in and out of areas with different temperatures, humidities, and air movements. Physical activity and exposure to solar radiation also affect surface body temperature. Metabolic processes continually produce heat within the body, even in the resting condition.

The body normally loses heat by radiation, convection, and evaporation of water from its surfaces. Ambient temperature, air movement, and humidity are important in determining the efficiency of heat loss in this manner. Air movement affects convection, and both air movement and humidity affect evaporation.

When the heat content of the body increases or decreases, the thermoregulatory mechanisms become active. These mechanisms involve interactions between the sweat glands and the nervous, hormonal, cardiovascular, and respiratory systems and are collectively termed the thermoregulatory system. In hot weather, the sweat glands become active to facilitate cooling of the skin by increased evaporation. The capillaries dilate to bring more blood to the body surface for cooling; the respiratory rate, blood volume, and heart rate increase.

When the ambient temperature is cold enough to accelerate heat loss, the cold sensors activate the regulatory mechanisms. There is vasoconstriction to conserve heat. Shivering generates heat in the muscles, and the basal metabolic rate increases. There is increased cardiac output, stroke volume, and blood pressure (Buskirk 1978).

There may be adverse effects of thermal stress if any part of the thermoregulation mechanism fails or if the stress is great enough to overwhelm the system and active measures are not taken to bring body temperature back to normal. Generally, however, if the stress is not too great, healthy individuals adjust and acclimate to the new temperature fairly rapidly and adequately. After 5–10 days of continued heat stress, the body temperature and pulse rate are near normal. By about 14 days, blood volume and venous tone are approximately normal, and by about 3 weeks, a new equilibrium seems to be established (Lind 1964; Lee 1968). If the heat stress is removed, most of the acclimation appears to be lost within a very few days. Whether there is any residual acclimation is not certain (Lind 1964). The way in which acclimation is accomplished and lost is not fully understood and needs more study (Lee 1968).

The studies on acclimation have usually been done either with artificially heated or cooled chambers or on people who have moved (suddenly been exposed) to hot and cold climates. Research to date does not seem to be strictly applicable to a situation in which a very gradual temperature change occurs, which may be the case in a CO₂-induced climate change. Nor is there much information on whether, if the thermoregulatory system is frequently or for long periods activated to counteract extreme temperatures (either hot or cold), this might eventually damage any of the components of the system (for example, the circulatory system). That is, it is not known whether one climate is more or less stressful than another during a lifetime.

If a CO₂-induced climate change increases the variability of weather and the occurrence of heat waves, then it appears probable that acclimation will not be adequate to prevent morbidity and mortality of some people, particularly the elderly and those who have diseased circulatory systems (see Section 7.4.2).

There may be many subtle differences between people living in different climates. For example, there are seasonal variations in conception that differ with climate and that could be considered to be physiological adaptation. In Chile, conception has been related to temperature, with the highest temperature coinciding with the peak of conception, except in the northern and southern extremes of that country, where there appears to be no seasonality for conception (Hajek et al. 1981). Macfarlane (1970) found a seasonal relation to the rate of conception in many areas of the world. He found that in cool, temperate climates maximum conception rates occur at a mean monthly temperature of 14°–16°C and minimum conception rates occur at 23°C. In warm, temperate climates the maximum conception rate is at 13.6°C, and the minimum is at 23°C; in the tropics, the maximum is 26°C and the minimum is 28°C. He states that humidity in the hotter regions (above 25°C) is an important factor in depressing the conception rate. He believes that the finding of different conception rates at different temperatures in different climates is *prima facie* evidence of reproductive adaptation to environmental temperatures. Holiday seasons and other cultural activities probably have influence on conception, but he suggests that ambient temperature and emotional influences on the female hormones related to fertility may play an important part in the seasonality of conception.

Other researchers also found seasonal patterns in birth rates. In general, conception seems to be lowest in hot weather, although there are some unexplained differences between the countries studied (Cowgill 1966; Calot and Blayo 1982); for example, seasonal patterns in the United States and Canada differ from those of Northern Europe. Seiver (1985) found that the seasonality of birth rates in the United States was most pronounced in the southern (hottest) States and that after air-conditioning became common, the maximum and minimum in birth-rate curves in the southern States became less pronounced. The reasons for the effect of hot weather on conception have not been precisely determined. However, in animals (Johnston and Branton 1953; Glover 1956; Venkatachalam and Ramanathan 1962) it has been found that sperm counts are depressed by increases in scrotal temperature. A study of human sperm (Tjoa et al. 1982) found that, in Houston, Texas, sperm counts were lowest in the summer despite widespread availability of air-

conditioning. Becker (1981) speculates that fecundity of women may change seasonally. Bernard et al. (1978) among others speculate that intercourse may be less frequent in uncomfortably hot weather. Shimura et al. (1981) hypothesize that seasonal diseases may have an influence on conception. However, cultural, socioeconomic, and behavioral factors also have some influence on seasonal patterns of conception. For example, Cowgill (1966) believes that urbanization has modified the seasonal pattern.

Active measures are taken by humans to minimize thermal stress. These include heating and cooling indoor environments, modifying clothing and food type and intake, and modifying physical activity.

A number of studies have investigated the possibility of genetic differences in races who have lived for many generations in very cold or very hot climates. It appears that there are no appreciable physiological changes that specifically adapt races to extreme climates, although cultural practices (e.g., types of clothing, housing, food) mitigate the effects (Newman 1975b). Thus, it would not be expected that genetic selection, over a number of generations, would assist in physiologically adapting humans to a CO₂-induced climate warming.

7.3.2 Physiology and Biochemistry

Several studies of human biochemistry and physiology have found seasonal changes in some of these parameters. Blood volume increases in the summer and decreases in the winter (Doupe et al. 1957). Fibrinogen (protein in blood clots) levels have been found to be higher in warm weather than in cold weather (Tromp 1972). Some of the hemostatic (blood-clotting) factors of the blood seem to vary seasonally (Bull et al. 1979). Seasonal variations have been found in body weight (Billewicz 1967). In a London study, blood pressure was found to be highest in April and May, and lowest in September (Rose 1961). In some studies, the basal metabolic rate has been found to be higher in winter than in summer (Carlson and Hsieh 1965; Matsui et al. 1978). Some of these changes may be related to thermoregulation, but the reasons for others are unclear.

Although there have been attempts (Bull et al. 1979) to relate some of these changes in biochemical and physiological seasonal variations to the seasonality of mortality in some diseases, the relationships are far from clear, and the effects of changes in climate are uncertain.

7.3.3 Birth Defects

Seasonal incidence of certain congenital malformations has been found (McKeown and Record 1951; Wehrung

and Hay 1970; Cohen 1971); whereas in other malformations, seasonality has not been found (Slater et al. 1964). In one study the United States was divided into four climate zones, and differences among these zones were found (Wehrung and Hay 1970). Cohen found similarly shaped curves in several countries and two U.S. States (winter peak, summer trough); in Australia the monthly pattern was essentially reversed. Other investigators, although they found a seasonal relationship to the occurrence rate of malformation, concluded that variations in climate were associated with only a small proportion of the seasonal variations (Elwood and MacKenzie 1971). Seasonal variations in hormones (possibly related to climatological variables), toxic metals, and infectious diseases have all been suggested as causes of the seasonal variations in these malformations. Regarding infections, however, McKeown and Record (1951) found no record of a specific fever in mothers during pregnancy relating to birth defects.

The birth months of people later diagnosed as schizophrenic were found to have a highly significant peak, most marked in March and April (Torrey et al. 1977). This seasonality was stronger in New England and the Midwest than in the South; it was also found in Northern Europe. Pulver et al. (1981) also found that in Monroe County, New York, there was an association between season of birth and risk of schizophrenia. In addition to seasonally varying factors that may damage the central nervous system, they point out that mothers of schizophrenic patients may be more likely to conceive in early summer than are other women. Nutritional, genetic, environmental (e.g., climatological influence on the estrous cycle of women), and infectious disease factors have all been suggested as possible agents.

It appears that climatological factors may have some, either direct or indirect, influence on birth defects; however, the precise relationships are very difficult to characterize, and the effects of a CO₂-induced climate change would be very difficult to predict considering the current lack of knowledge about the primary causative agents.

7.4 MORTALITY AND MORBIDITY RELATED TO CLIMATE/WEATHER

7.4.1 Seasonality of Mortality and Morbidity

Historically there has been a seasonal pattern for death rates, presumably due to climate and weather influences. These patterns have been changing during the time in which reasonably good records have been kept. This is illustrated for three countries in Figure 7.2, from

Momiyama-Sakamoto et al. (1977). These data are for all deaths in the particular country and are therefore for a mixture of climates, although the three countries have roughly the same mean annual temperature. The differences among the countries are attributed to differences in their rates of development (hygiene, medical care, nutrition, central heating, housing, etc.). The prominent summer peaks in the 1890–1930 curves for Japan were principally due to communicable diseases. The winter peaks occurring in the later periods in all three countries are attributable principally to diseases of the aged, for example, heart and cerebrovascular diseases. For comparison, Momiyama and Kito (1963) examined the seasonality of death in Egypt, a relatively underdeveloped country. They found that there was a high summer mortality from gastroenteritis, dysentery, and avitaminosis, and a low (compared with the United Kingdom and Japan) mortality from heart disease and stroke (cerebrovascular disease). They did not discuss the age of the population and climate effects, but these may have been important factors in the cause of death. A warm climate may be more favorable for the propagation of airborne and waterborne communicable diseases. In areas where such diseases are prevalent, the mortality rate among the young is high, which leaves a smaller elderly population to die of the diseases that are common to the elderly.

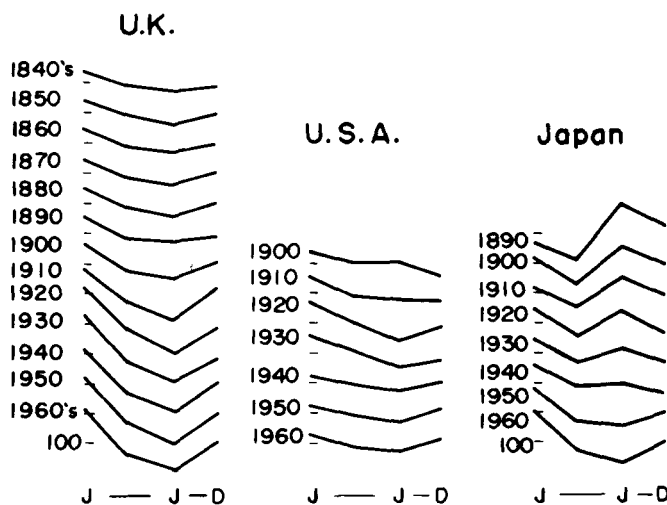


Figure 7.2. Historical changes in seasonal variation patterns of mortality in the United Kingdom (1840–1960), the United States (1900–1960), and Japan (1890–1960). Curves run from January to December. Monthly death index = (monthly mortality)/(annual mortality) $\times$ 1200. This method of calculating the death index arbitrarily sets the annual average death index at 100 (the tick marks on the curves); thus the parts of the curves above the tick marks are higher than the annual average for that period and vice versa. Source: Momiyama-Sakamoto et al. (1977).

In other studies Momiyama and Katayama (1966, 1967, 1972) examined the contribution of various age groups to the seasonality of death. Infant mortality contributed greatly to the summer peaks in the earlier years studied, but by the 1970s peaks in infant mortality had become much smaller. Infant mortality was spread rather evenly throughout all the seasons. By the 1970s the largest contributors to the winter peaks were deaths of people 60 years of age and older, predominantly from heart and cerebrovascular diseases.

7.4.1.1 Mortality From All Causes

A number of investigators have found correlations between mortality from various diseases and weather and climate variables. Bull and Morton (1978) related death rates to the mean monthly temperatures in England and Wales. Mortality from vascular, heart, and respiratory diseases was most highly related to temperature, whereas deaths from asthma, cancer, and leukemia were related to temperature the least. Rosenwaike (1966) found in the United States, for the period 1951–1960, that most diseases peaked in winter. The exceptions were cancer, which had no peak, and certain diseases of early infancy, which peaked in the summer.

In general, mortality from all causes in the temperate and subtropical zones of developed countries peaks in winter when temperatures are coldest and drops to its lowest levels when temperatures reach about 21°–27°C. However, if temperature goes much above 27°C, there may be upsurges in mortality. A generalized curve depicting this situation is shown in Figure 7.3.

7.4.1.2 Mortality From Heart Disease

Although this situation seems to be reversing somewhat, mortality from heart disease increased over several past decades. For this reason, researchers have looked for

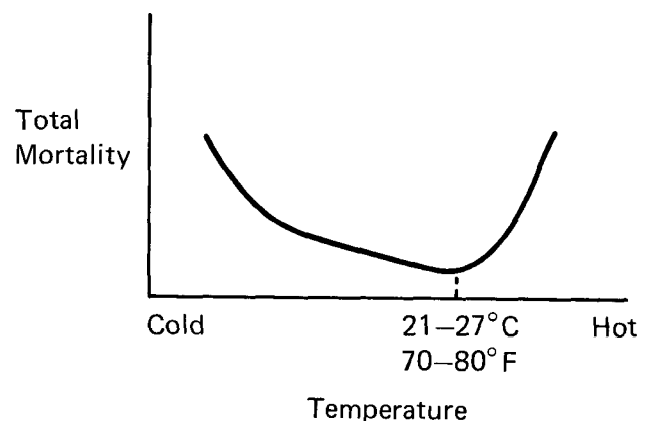


Figure 7.3. Generalized relationship between mortality and ambient temperature.

contributing causes, and a number of studies of mortality from these diseases, relative to weather and climate variables, have been carried out. Results of a few of these studies are summarized below to illustrate the knowledge and the questions that are emerging.

Ambient temperature over a fairly wide range (below about 24°C) and in several midlatitude countries has been found to be negatively correlated with mortality from heart disease. That is, a rise in the mean monthly temperature is associated with a fall in mortality (Rose 1966; Dunnigan et al. 1970; Campbell and Beets 1979). Over the temperature range from -1° to 21°C (30°–70°F), Rose obtained a correlation coefficient of -0.95 between the logarithm of the monthly mortality index and temperature. West and Lowe (1976) found that in London, there was a 2.5% increase in mortality for each 1°C drop in mean monthly temperature when temperatures were between 2.3° and 17.9°C. Dunnigan also found a winter peak for heart disease patients admitted to the hospital but discharged alive. The change in the rate of mortality from heart disease per degree of temperature change appears to be different in different climates. Figure 7.4, from Anderson and Le Riche (1970), compares England and Wales with Australia (a hotter climate) and Ontario and Denmark (mean annual temperatures approximately equivalent to that of England, although Ontario is hotter in the summer and colder in the winter). They suggest that the amount of intercurrent respiratory disease (which may be higher in one country than in another) may be responsible for the differences among countries. However, other investigators (Rogot 1974; Bainton et al. 1977) have found that intercurrent respiratory disease had only a minor influence on the relationship between temperature and heart disease mortality. States (1977) compared mortality in Pittsburgh, Pennsylvania (temperate climate), and Birmingham, Alabama (subtropical climate), and related mortality to meteorological variables. He found deaths in Pittsburgh from ischemic heart disease to be highly correlated with weather (directly correlated with temperature change), but weather was poorly correlated with deaths from cerebrovascular diseases. The reverse was true in Birmingham. The correlation of mortality with weather variables was significant in both cities, but it was lower in Birmingham.

There was a direct relationship of interdiurnal change in barometric pressure to mortality (for white males, for people over 70, and for death from ischemic heart disease). States (1976) surmises that the change in barometric pressure itself is probably not as important as the fact that it is an indication of more profound meteorological changes, such as changes in air mass. Hansen (1970) found that the more abrupt the change in barometric pressure, the higher was the probability for

peripheral arterial embolism to occur; this observation did not change with seasons.

Even though heart disease mortality gradually declines as the temperature increases, it increases rather abruptly during periods of very hot temperature. The exact temperature at which this abrupt increase occurs appears to differ a few degrees in different regions. Figure 7.5, from Rogot and Padgett (1976), illustrates this for a number of cities in the United States. The

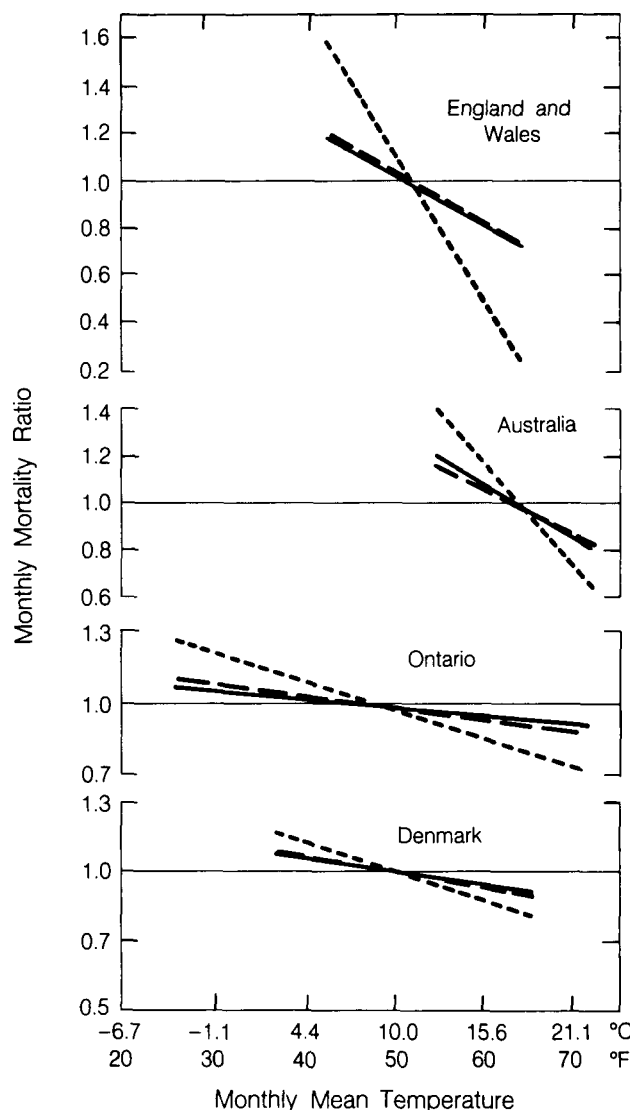


Figure 7.4. Relationship of monthly mortality ratio to monthly mean temperature. Monthly mortality ratio is the ratio of death rate/mo to the mean death rate/yr. Both rates were expressed in the number of deaths/d to allow for variations in number of days in each month. Symbols: (—), arteriosclerotic and degenerative heart disease (ICD 420–422, 7th Revision World Health Organization 1955); (---), vascular lesions of the central nervous system (ICD 330–334, 7th Revision World Health Organization 1955); (-.-), diseases of the respiratory system (ICD 470–527, 7th Revision World Health Organization 1955). Source: Anderson and Le Riche (1970).

cities on the left are in areas that have snow, those on the right are in areas where snow is unusual. Note that this figure uses numbers of deaths; therefore, death rates cannot be compared for the different cities.

Other meteorological variables also have been examined for their relationships to heart disease mortality. Although these variables show a relationship to

mortality, it should be noted that the effects are due to synergistic actions with other variables, especially temperature and wind; that is, it is the heat load on the body that is important.

Relative humidity has been found to be positively related to mortality in both hot and cold weather (Dudley et al. 1969; Rogot 1974; Campbell and Beets 1979).

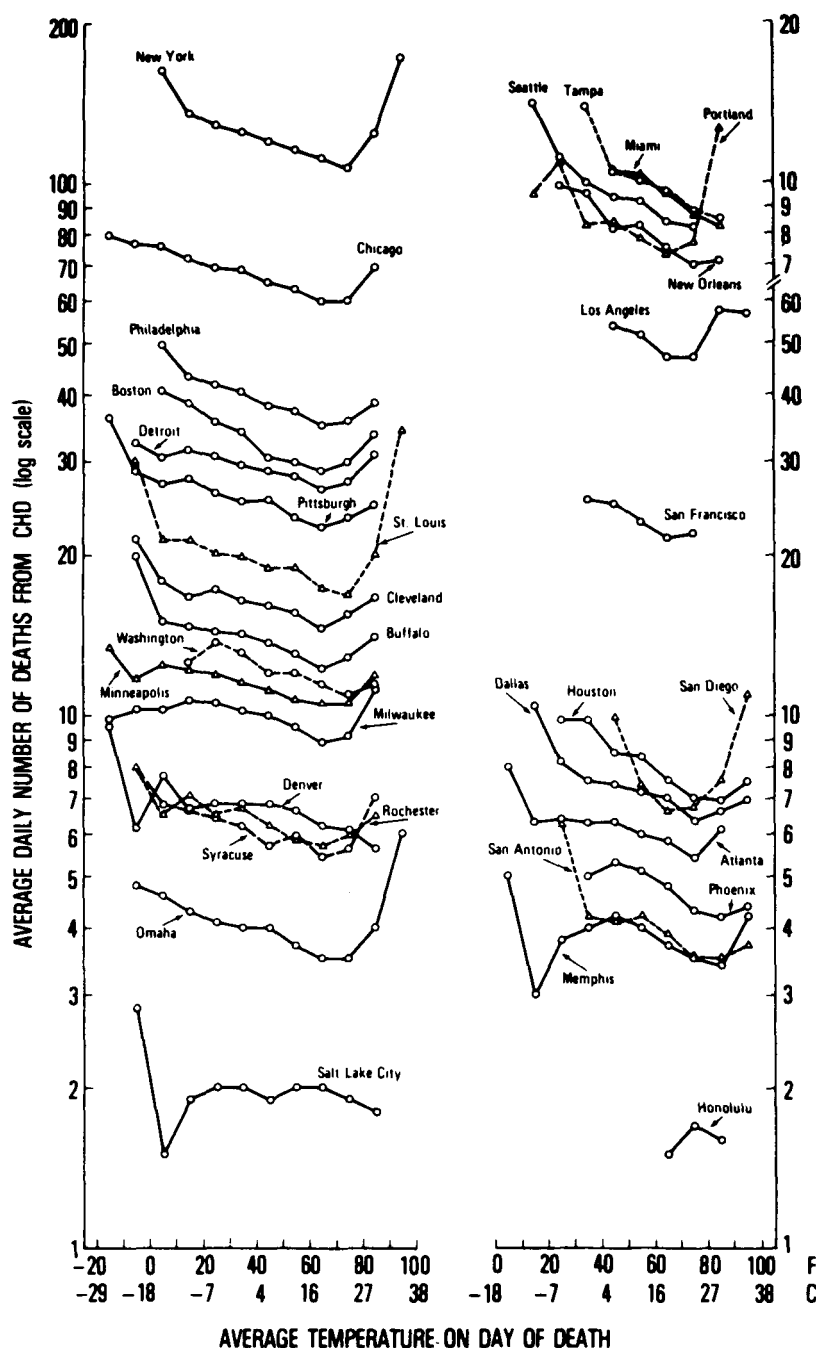


Figure 7.5. Relationship of temperature to heart disease mortality. Average daily deaths from coronary heart disease by average temperature on day of death for 32 selected Standard Metropolitan Statistical Areas in the United States from 1962 to 1966. Source: Rogot and Padgett (1976).

Anderson and Le Riche (1970), in their comparisons of countries with different climates (Figure 7.4), pointed out that during the winter months, England, Wales, and Australia, with the steepest regressions, had damper winters than Denmark and Ontario, thus implying that humidity may have modified the effects of temperature.

The relationship of *rainfall* to mortality from heart disease has been studied by several investigators. For England and Wales (Rose 1966; Bull 1973) and for Memphis, Tennessee (Rogot and Blackwelder 1970), no significant correlations were found; however, a positive correlation was found by West and Lowe (1976) and Roberts and Lloyd (1972) for England and Wales, and by Rogot (1974) for Chicago.

Periods with heavy *snowfall* had relatively high rates of mortality from heart disease in Minneapolis-St. Paul, Minnesota (Baker-Blocker 1982), Chicago, Illinois (Rogot 1974), selected U.S. metropolitan areas (Rogot and Padgett 1976), and Toronto and Ontario in Canada (Anderson and Rochard 1979). It is probable that part of the effects of snowfall is due to increased physical activity in the cold. For the days of snow and immediately following, Anderson and Rochard found a larger increase in death rate for men under 65 than for those over 65. They pointed out that the men under 65 probably both worked and felt compelled to shovel snow, whereas those over 65 (presumably retired) did not feel compelled to be active in the snow.

Windspeed in January was found to have a positive correlation with the rate of mortality in 143 U.S. metropolitan areas (Campbell and Beets 1979). However, from studies carried out in England and Wales (Bull 1973) it was concluded that the relationship between windspeed and mortality was of doubtful biological significance.

Prefrontal weather was found to coincide with increases in total mortality, and *postfrontal* weather was found to coincide with decreases in total mortality in the North-Central and Northeastern States in the United States (Driscoll 1971). In three different areas of the world—Japan, Houston, Texas, and Israel—Cech et al. (1976, 1977, 1979a, 1979b) found increased mortality due to heart disease at times that are typical for the intrusion of polar air during the winter anticyclones that follow cold fronts.

7.4.1.3 Mortality From Cerebrovascular Diseases

Cerebrovascular diseases, including strokes, also have been related to meteorological factors. Figure 7.6 shows the relationship of stroke mortality to temperature (from the study of Rogot and Padgett [1976]). The lowest mortality occurred between 15.6° and 26.6°C (depending on the city); then there was a sharp rise as the temperature increased. These data are presented

as average daily deaths; therefore, although the shape of the curves can be compared, the rate of death in cities, with different climates cannot be compared. Bull (1973) and Bull and Morton (1975, 1978) have obtained essentially the same results. For England and Wales, from -10° to +20°C, they found a nearly linear decrease in the number of deaths as the temperature increased. Above and below this range, the death rates rose sharply, particularly in the older age groups. The investigators related mortality to temperatures during the 3 to 4 days before death.

Rogot and Padgett (1976) found that during periods of snow there was a higher than expected stroke mortality. Bull (1973) found that wind speed had no significant relation to stroke mortality.

Cech et al. (1979b) found that increased stroke mortality was related to intrusions of the winter anticyclonic synoptic system, that is, low temperature, low relative humidity, and high wind speed and barometric pressure.

Momiyama and Katayama (1972) related the number of deaths from strokes in London, Tokyo, and New York City for 1960–1964 to temperature. These data are shown in Figure 7.7. There is a negative relationship between stroke and temperature in all three cities. However, New York, with the lowest temperatures of the three cities, also had the least steep slope. The authors attributed this to better central heating in New York, which probably better protected the susceptible people from extreme weather.

7.4.1.4 Mortality and Morbidity From Respiratory Diseases

Rosenwaik (1966), using data from the United States, found the highest number of deaths from influenza and pneumonia (combined) and bronchitis in December and January, and low death rates in June, July, and August. Bull and Morton (1978), using data from England, Wales, and New York, found high correlations between temperature and deaths from lobar pneumonia and acute and chronic bronchitis. The relationship was nearly linear and inverse from about -5° to about 20°C. When segregated into ages above and below 60 years, the slope of the line was much steeper for those over 60 years. Rogot and Blackwelder (1970), using data from Memphis, Tennessee, found that daily deaths from respiratory diseases were highest at low temperatures (<4°C) and gradually decreased up to temperatures of about 23°–24°C, and then abruptly increased. The data quoted above were not specifically related to epidemics, but epidemics of influenza, which at times have killed thousands of people, occur in the winter both in the Northern and Southern Hemispheres and during the rainy season in the tropics. Research

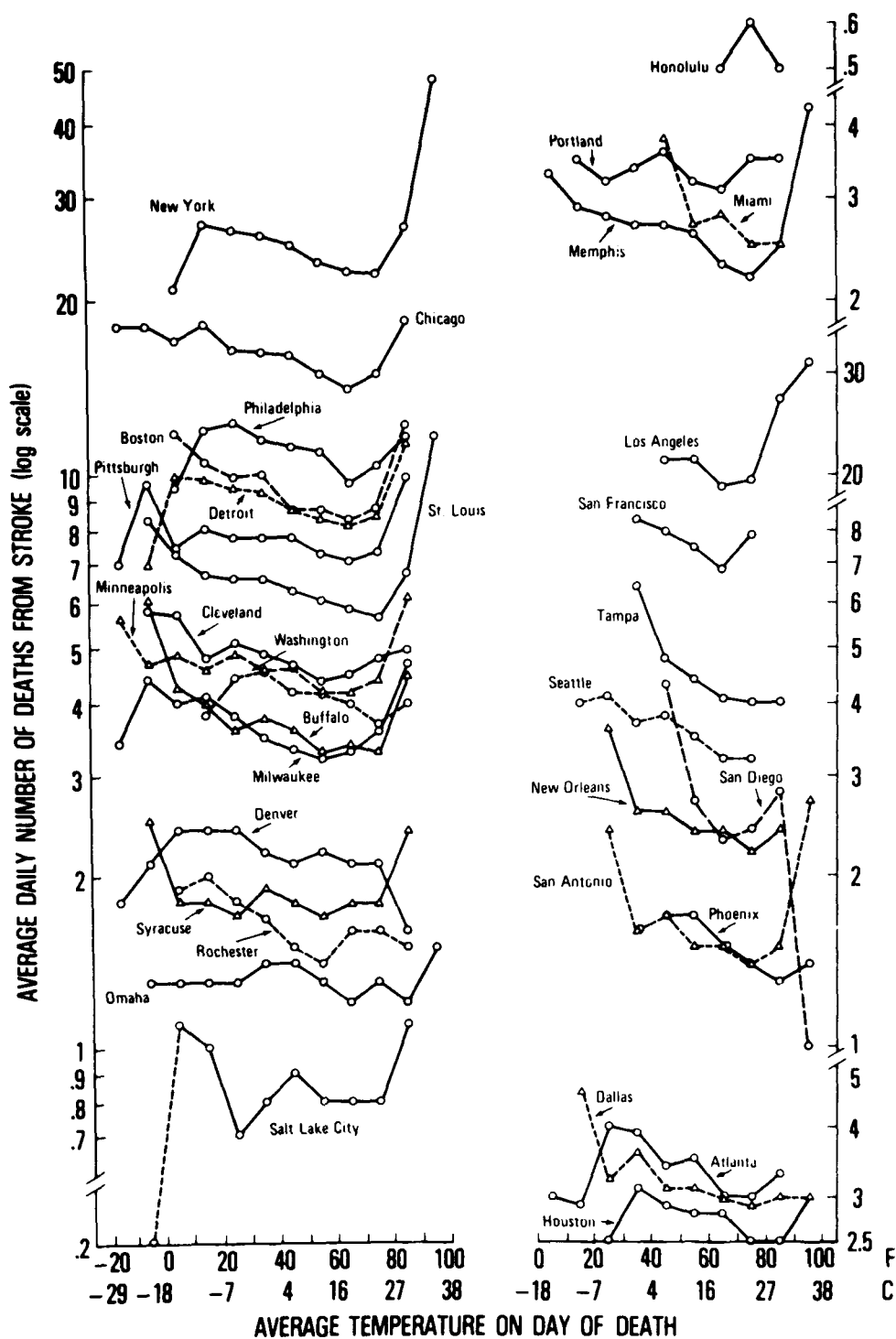


Figure 7.6. Relationships of temperature to stroke mortality. Average daily deaths from stroke and average temperature on day of death for 32 selected Standard Metropolitan Statistical Areas in the United States from 1962 to 1966. Source: Rogot and Padgett (1976).

attempting to explain the relation of influenza epidemics to specific weather variables has been unproductive (Hope-Simpson 1979).

Goldstein (1980) studied asthma attacks in New Orleans, Louisiana, and New York City. Asthma is related to airborne agents such as spores and molds, and there seems to be a relationship to meteorological variables. Goldstein found that clusters of attacks (epidemics) are preceded, by 1 to 3 days, by the passage of a cold front followed by a high pressure system. It is suggested that the fronts bring in new air containing astmatogens and that the high pressure system tends to result in stagnant rain-free conditions that retain the airborne particles. Tromp (1980) also implicated cold

fronts in the onset of asthma in Europe and added that heat stress combined with high humidity may instigate asthma attacks.

7.4.1.5 Mortality From Cancer

Mortality from cancer (data pooled from several types) in England and Wales (Bull and Morton 1978), Memphis, Tennessee (Rogot and Blackwelder 1970), and the entire United States (Rosenwaike 1966) was found to have very little association with temperature. The little association present may be due to temperature stress on people who are already terminally ill.

Regarding the onset of cancer, there are two types of cancer in which meteorological influence seems apparent. The first is skin melanoma, which is thought to be related to the amount of solar radiation (ultraviolet radiation, which is not expected to change under a CO₂-induced climate change unless there is a large change in cloud cover), but may also have some relationship to female hormones because, especially under the age of 55, the incidence of skin melanoma is higher in women than in men (Scotto and Nam 1980; Cohen 1983; and Cohen et al. 1983). Cultural differences may also affect the rate of incidence of this cancer. The frequency of exposure and the amount of skin exposed to solar radiation differ according to culture. The male/female ratios for melanoma differ with climate, so there may be a climate effect on hormone balance; although this is currently only theoretical (Cohen 1983). Breast cancer detection (diagnosis) also has a seasonality that varies somewhat in different climates and may be related to seasonal changes in hormones. The seasonality of hormone levels to a certain extent may be related to ambient temperature, but this is an area in which further investigation is needed (Cohen et al. 1983).

Burkitt's lymphoma is a cancer that has been found to have a definite relationship to climatological factors. It is found in areas where the temperature is always above 15°C, and the annual rainfall is more than 50 cm. The Epstein-Barr virus is the etiological agent; however, the virus is not limited to the climate where the lymphoma is found. It was eventually found that the climatological factors favor malaria and that malaria depresses the immune system. The depressed immune system allowed the virus to initiate lymphoma. The tumor is common only in those areas where malaria is highly endemic. Thus, in this case, if a CO₂-induced climate change causes new areas of the world to have temperatures continuously above 15°C and rainfall of more than 50 cm, these areas might also become endemic for Burkitt's lymphoma (Burkitt 1983), unless malaria-carrying mosquitos are well controlled.

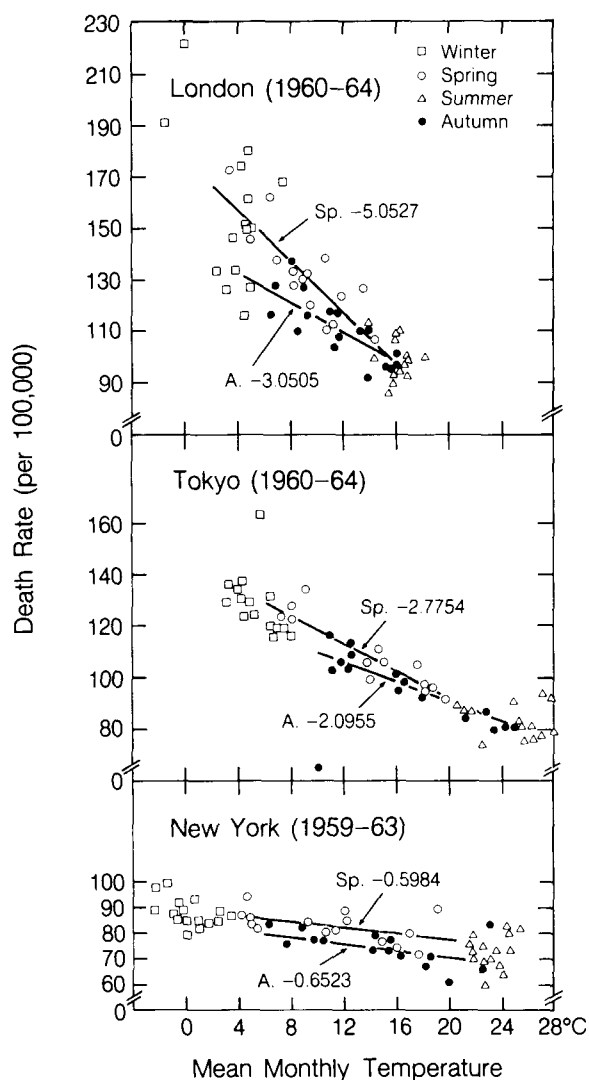


Figure 7.7. Comparison of the relationship of temperature to death rate from cerebrovascular diseases in London, Tokyo, and New York City. Sp is the regression coefficient for spring (3 months); A is the regression coefficient for autumn (3 months). Source: Momiyama and Katayama (1972).

7.4.1.6 *Fetal and Infant Mortality*

Perinatal (late fetal and less than 7 days of age) mortality and preterm delivery have been shown in the United States to have a seasonal variation with major maxima in July and August, a smaller peak in January, and a minimum value in March and April. It has been suggested that this may partially be an indirect effect of meteorological variables because of infections that have a seasonal distribution (Slatis and DeCloux 1967; Janerich et al. 1971; Keller and Nugent 1983). However, protection of infants against exposure to extreme temperatures is very important. In England an earlier seasonal trend in perinatal deaths has disappeared, but there is still a relationship between the variation in death rate at 1–11 months of age and temperature (Hare et al. 1981). In Australia, there is a high correlation between an index of heat stress and infant mortality, with the hotter areas having higher mortality (Dasvarma 1980). A seasonal effect has been noted in spontaneous abortions, which peak in the spring (McDonald 1971) and may be related to seasonally occurring infections.

Selvin and Janerich (1971) found a seasonality in birth weights, with high-weight infants born in March, April, and May and low-weight infants born in June, July, and August. They speculate that the low birth weight seen in the summer may have been due to environmental factors occurring during early gestation in the fall and early winter.

7.4.1.7 *Mortality From Other Causes*

Deaths in the United States of people with diabetes, tuberculosis, some renal diseases, cirrhosis of the liver, and senility (plus ill-defined conditions) are higher in winter than in summer (Rosenwaike 1966). In England and Wales deaths from gastric and duodenal ulcers and genitourinary diseases have been related inversely to mean temperatures (Bull and Morton 1978). In these diseases there is generally a prolonged illness preceding death, and it might be expected that any stress (including low temperatures) would precipitate death in people already very ill. However, the onset of insulin-dependent juvenile diabetes has been shown to have a seasonal variation (peaks in the summer), which has mirror image patterns in the Northern versus the Southern Hemispheres (Durruty et al. 1979; Fleegler et al. 1979). Aside from juvenile diabetes, a CO₂-induced climate warming may prolong the lives of people with some of these diseases, but the effect would probably be small.

In the United States suicides tend to peak between March and May, and homicides have two peaks: July–September and December. Motor vehicle accidents are lower in the first half of the year (January–June) than in the last half, with the highest rate being in October

through December. Nonmotor vehicle accidents are highest in June and July, probably because these months are peak vacation times (Rosenwaike 1966). Although meteorological factors may have some influence, these causes of death are so interrelated with psychological and cultural factors that it would be difficult to determine the quantitative effects of CO₂-induced climate changes.

Thus, seasonal changes in weather variables have an important role in morbidity and mortality. In less developed countries there still is a large influence on health from communicable and parasitic diseases, some of which peak in the summer and many of which are greatly influenced by weather elements (see Sections 7.6 and 7.7). In the more highly developed countries, where infectious and some parasitic diseases have been largely controlled, the effects of cold winters and hot summers are primarily in people with deficient thermoregulatory systems and, secondarily, in people who have undue exposure to, or activity in, extreme temperatures and in which the thermoregulatory system, although it may be functioning properly, is overwhelmed. It is uncertain how much the underlying climate is related to long-term (possibly damaging) stress on the thermoregulatory system, or how it relates to physiologically adapting people to better withstand thermal stress.

A first assumption might be that, if CO₂-induced climate change resulted in warmer winters, in currently temperate and cold zones, the life of some people might be prolonged. However, hotter summers might, to some extent, offset this. Hotter summers, in subtropical and temperate climates, will most probably increase heat-related deaths. In addition the other weather elements, that is, humidity, precipitation, and wind, act synergistically with temperature to modify (either beneficially or detrimentally) thermal stress. Thus, the rate of climate change, the regional and seasonal extent of changes in the climate and the weather elements, and the variability of weather are needed to predict the effects of CO₂-induced climate change on people with organic diseases.

7.4.2 *Heat Waves*

There is currently no information about possible changes in the variability of weather resulting from a CO₂-induced climate change. If variability decreases, even though the average temperature may be higher, there should be fewer heat waves. If variability increases there may be more heat waves. Because of these uncertainties and because studies of heat waves give some insights into the effects of higher than normal temperatures, these studies may be relevant to the effects of a CO₂-induced climate change.

Death rates can increase markedly as a result of heat waves, and the peaks correlate with maximum daily temperature 1–2 days before death; that is, there is a 1–2 day lag between the hottest temperatures and the peak in death rate (Bridger and Helfand 1968; Oechsli and Buechley 1970; Ellis 1972; Ellis et al. 1975). Figure 7.8 from an early study by Gover (1938) shows the death rates and temperatures in 1936, during excessive heat, for various cities in the United States. These are compared to normal death rates and temperatures (non-heat wave years).

Heat waves acute enough to cause illness and increase death rates vary in their meteorological characteristics from year to year in the same region and from region to region in the same year. The demographic characteristics also can vary appreciably from city to city and within the same city over a few years' time. Thus, it is difficult to compare the effects of one heat

wave with those of another. Table 7.1 illustrates this with temperature and mortality data from heat waves in New York, Los Angeles, and St. Louis. In comparing excess deaths in the 1966 heat wave, note that the population of New York was about 10 times that of St. Louis, and that the heat wave lasted about twice as long in St. Louis. The most important meteorological factor is an increase in mean daily temperature of several degrees above normal for the region lasting for several days to several weeks (Bridger and Helfand 1968; Oechsli and Buechley 1970; Ellis 1972; Ellis et al. 1975). The length of the heat wave, maximum daytime temperature, minimum night temperature, humidity, and air movement all contribute to the effect on humans because they influence body temperature, and thus to the burden on the thermoregulatory system.

Illness (heat stroke, heat exhaustion, etc.) may occur in healthy people who are overexposed to, or

Table 7.1
Data from Heat Wave Studies

Ellis and Nelson (1978): New York Heat Wave, August 1975		
Length of heat wave	(July 31-August 5)	6 days
Average maximum daily temperature	(July 31-August 5)	92.2°F (33°C)
Average minimum daily temperature	(July 31-August 5)	74.3°F (23°C)
Average dew-point temperature	(July 31-August 5)	68.5°F (20°C)
Average daily mortality	(August 1-6)	293
Excess deaths per/day (compared to mortality in the same weeks in 1973 and 1974)	(August 1-6)	94
Schuman (1972): New York City Heat Wave, July 1966		
Length of heat wave		14 d
Temperature: 12 days		>90°F (32°C)
Total excess mortality (increase over normal)		1181 (36.3%)
Excess deaths per day		84
Schuman (1972): St. Louis Heat Wave, July 1966 ^a		
Length of heat wave		28 d
Temperature: 24 days		>90°F (32°C)
Total excess mortality (increase over normal)		618 (55%)
Excess deaths per day		22
Oechsli and Buechley (1970): Three Los Angeles Heat Waves		
September 1939		
Length of heat wave:		7 d
Average maximum daily temperature:		103.4°F (40°C)
Total excess mortality (9 d):		546
Excess deaths per day (9 d):		61
September 1955		
Length of heat wave:		7 d
Average maximum daily temperature:		103.5°F (40°C)
Total excess mortality (9 d):		946
Excess deaths per day (9 d):		105
September 1963		
Length of heat wave:		4 d
Average maximum daily temperature:		106°F (41°C)
Total excess mortality (8 d):		580
Excess deaths per day (8 d):		72

^aNote: population of St. Louis at the time of this study was approximately one-tenth that of New York.

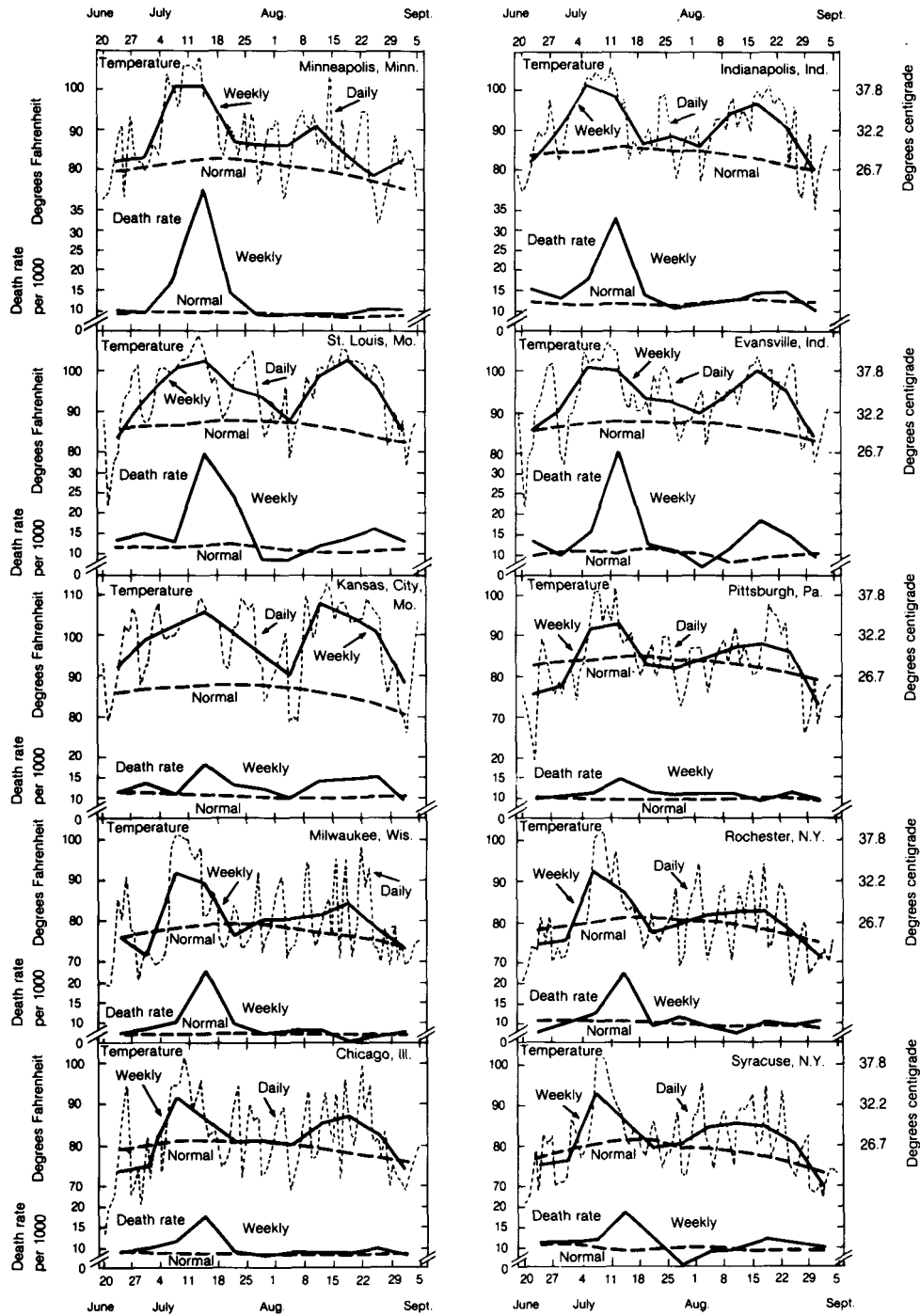


Figure 7.8. Weekly death rate from all causes (annual basis) and daily and average weekly maximum temperature for 10 cities in an area of extreme temperature for 11 summer weeks of 1936. Source: Gover (1938).

overactive in, the heat. However, the majority of excess deaths that occur during heat waves are primarily from other illnesses in which heat stress accelerates death. Infants, the elderly, and people already ill, in particular those with circulatory problems, are most at risk during excessive heat (Schuman et al. 1964; Oechli and Buechley 1970; Bridger et al. 1976; Jones et al. 1982). Tables 7.2 and 7.3 illustrate the age influence on the death rate. Older people are more at risk because the main stress is on the circulatory system and many older people have heart and vascular diseases. Because of circulatory problems their thermoregulatory systems are not as efficient as those of younger people (Crowe and Moore 1973; Ellis and Nelson 1978). Excess mortality in infants less than 24 hours old has been noted (Bridger et al. 1976); this is probably because their thermoregulatory systems are not yet functioning adequately to counteract the heat.

The illnesses of adults affected by heat are predominately ischemic heart disease (Ellis and Nelson 1978) and cerebrovascular lesions (Schuman et al. 1964). In some regions or in some years the percentage rise in death due to heart disease was found to be higher (Ellis et al. 1975); in other regions or years cerebrovascular diseases accounted for more deaths (Bridger and Helfand 1968; Ellis and Nelson 1978). Whether this difference is due to the weather preceding the heat wave, the characteristics of the particular heat wave, or nonclimatic influences is unknown.

There has been speculation that most people who die as a result of heat waves would have died very soon even without this stress. Some investigators state that

there was no drop in overall mortality after heat waves, which would have compensated for deaths during heat waves (Henschel et al. 1969; Schuman 1972; Ellis et al. 1975). In Gover's data (Figure 7.8) only 3 of the 10 cities show a drop below normal within a few days after the first heat wave, and these were fairly small and probably not significant. However, Schuman et al. (1964) examined data for deaths of people over 65 years of age from 108 cities in the United States and found an impressive drop in mortality 5 weeks after the heat wave. Thus, there is uncertainty regarding the extent by which life is shortened in those who die as a result of heat waves.

Determining the number of people who become ill because of heat stress but who do not die is difficult because these cases are generally not listed in public health records. However, it appears that at least as many become ill but survive as die (Cook 1955; Jones et al. 1982).

Within a region during a particular heat wave, investigators have examined various factors other than climate that seem to influence heat wave effects. Death rates increase much more in inner cities than they do in suburban and rural districts (Henschel et al. 1969; Schuman 1972; Jones et al. 1982). Several factors are probably involved here (see below), but the most predominant of these is thought to be urbanization, which has modified the climate (Clarke 1972a). There also may be relatively fewer air-conditioners or coolers per urban residence than in suburban residences. Daytime urban-rural temperature differences are small. However, the urban core retains heat at night because

Table 7.2
Number of Deaths per 1000 Population by Age, Sex, and Race in St. Louis, Missouri
for July 1966 (Heat Wave) and the Year 1965

Age Group (years)	Total	Sex		Race		Male		Female	
		Male	Female	White	Other	White	Other	White	Other
July 1966 (on annual basis)									
All Ages	27.1	29.2	25.3	30.5	21.0	33.7	21.4	27.8	20.6
Under 5	13.4	11.2	15.7	10.4	17.0	9.9	12.8	11.0	21.1
5 to 24	1.2	1.6	0.8	1.2	1.2	1.5	1.8	0.9	0.7
25 to 44	7.0	8.6	5.5	6.4	7.9	7.7	10.3	5.1	6.1
45 to 54	19.5	25.7	13.7	17.5	23.7	23.4	30.5	12.2	17.1
55 to 64	36.2	53.8	24.0	29.2	58.7	49.4	65.7	16.0	52.7
65 to 74	89.3	107.8	74.8	83.4	109.7	116.2	84.7	60.1	137.0
75 and over	231.1	236.7	227.6	246.5	167.9	247.8	192.2	245.7	151.9
Resident 1965									
All Ages	14.2	16.5	12.2	15.6	11.6	17.9	13.8	13.6	9.7
Under 5	8.0	8.6	7.4	5.7	11.0	6.2	11.6	5.1	10.3
5 to 24	0.9	1.2	0.6	0.7	1.1	1.0	1.5	0.5	0.7
25 to 44	3.6	4.6	2.7	2.4	5.6	3.1	7.5	1.8	4.1
45 to 54	10.4	13.4	7.6	8.2	15.1	11.4	17.8	5.5	12.5
55 to 64	20.3	30.0	13.3	17.6	29.2	28.1	35.6	10.4	23.7
65 to 74	45.7	61.0	34.0	42.8	56.7	80.3	63.6	30.4	49.8
75 and over	115.7	130.0	106.7	123.8	80.1	136.7	101.4	115.8	65.7

Source: Bridger et al. (1976).

Table 7.3
Mortality During Three September Heat Waves in Los Angeles

	1939	1955	1963
Number of Days of Excessive Heat	7	7	4
Maximum Temperature	41.7°C (107°F)	43.3°C (110°F)	42.8°C (109°F)
Day of Maximum Temperature	4	2	2
Day of Peak Mortality	5	3	5
Peak Mortality as Percentage of Expected (All Ages)	271	445	172
Peak Mortality as Percentage of Expected (50-54 Years)	245	307	140
Peak Mortality as Percentage of Expected (85+ Years)	570	810	257

Source: Oechsli and Buechley, 1970

of the lack of air movement, higher near-surface air temperatures, and greater heat load. After sunset, rural surfaces cool more rapidly than do urban surfaces, because soil and grass have lower heat conductivity and storage capacity than do brick and concrete surfaces. Large urban structures also lose heat more slowly than do single-family dwellings. More heat-stroke victims were found in upper levels of multistory buildings than in residences well shaded by trees and shrubs (Kilbourne et al. 1982). Thus it appears that the urban environment contributes substantially to excess morbidity and mortality.

The racial makeup of people who died in heat waves has been studied with apparent contradictory results. In some cases, white people seemed to have higher excess mortality (Bridger et al. 1976, see Table 7.2); whereas in other cases mortality in nonwhites was higher (Henschel et al. 1969; Schuman 1972), and in yet others, there apparently were no differences (Schuman et al. 1964; Bridger and Helfand 1968). These apparent contradictions may have resulted, for example, from methodological or socioeconomic differences.

Socioeconomic status has been found to be a factor in the death rate in heat waves. People in the lower socioeconomic status generally were found to have the largest increases in deaths (Buechley et al. 1972; Schuman 1972; Jones et al. 1982). However, these people live predominately in the inner cities, frequently in high-density, possibly inadequately ventilated housing, and probably a high percentage of this population perform manual labor in the heat.

The male/female ratio of victims of heat waves has also been examined but without consensus regarding results (Schuman et al. 1964; Bridger and Helfand 1968; Henschel et al. 1969; Schuman 1972; Bridger et al. 1976). Some of these studies were not age-adjusted,

which may have influenced the results because there are usually more women in the older age groups.

Some studies have suggested that widespread use of air-conditioning has reduced the effects of heat waves (Henschel et al. 1969; Oechsli and Buechley 1970; Kilbourne et al. 1982). However, one study (Buechley et al. 1972) found that the correlation between percentage of cases with air-conditioning and the mortality rate ratio in counties of the New York-New Jersey area, although significant and negative, was small. There is also some indication that residence in air-conditioned premises may interfere with acclimation to heat (Marmor 1975) and thus make people more vulnerable to heat when they are in non-air-conditioned environments. For example, a power outage during excessive heat might result in disproportionate numbers of deaths in people accustomed to air-conditioning (Bridger et al. 1976). Nonetheless, air-conditioning undoubtedly does lessen stress, thus protecting susceptible people when there are heat waves.

There are physiological adjustments to extreme heat (Wyndham et al. 1970; Folk 1974). However, the extent to which these mechanisms increase the heat tolerance of humans and modify morbidity and mortality for normal (for a particular climate) hot weather and for heat waves is uncertain. The data of Gover (1938), Figure 7.8, which were collected before air-conditioning had an appreciable effect, indicate that in the second heat wave of one summer the death rate was lower than in the first heat wave; this partly may have been due to the most vulnerable people being eliminated during the first heat wave. However, it appears that, at least partially, this lower death rate may have been due to acclimation acquired during the earlier part of the season.

Gover found that for particular weeks during the 5 years in her study, both normal temperatures and

death rates were higher in the south than in the north-central, north-Atlantic, and western areas of the United States. However, in 1 year in both the south and the north-central regions the weekly average temperature was 35.6°C (4°C above normal for the south and 7.6°C above normal for the north-central region). During this period the death rate in the south increased by only 12%; whereas in the north-central region it increased by 132%. Variables other than temperature were not examined, but Gover thought it was the excess over normal temperature rather than the actual temperature that was associated with the marked increase in weekly mortality and that acclimation had an influence.

Unfortunately, literature on heat waves is inadequate in relating the precise contributions of individual weather and climate variables to the increase in morbidity and mortality. First, weather conditions, that is, the length and intensity of the heat wave, the suddenness of its onset, the degree to which the temperature deviates from the normal for the season and the region, and the accompanying humidity differ with each heat wave. Second, different regions and the same region in different years may have different demographic characteristics; the data available to and the methodology used by investigators also can differ. Until the CO₂ issue arose, there was no reason to investigate the effects of a changing climate in a particular region; therefore, with the exception of temperature, climate and weather variables were not usually considered in the studies.

Lee (1980) reviewed models intended to relate climatological variables to human health and comfort and concluded that, of those developed so far, all had inadequacies. However, several indices have been used as predictors of heat stress. Quayle and Doehring (1981) discuss several of the indices and conclude that one, termed apparent temperature (Steadman 1979a, 1979b), is probably the most comprehensive. Steadman based his research on human physiology and clothing science, assuming a typical adult human in the shade and a base windspeed. He determined the rate at which heat is transferred from the body to the surrounding air (to keep body core temperature at approximately 37°C) at different temperatures and humidities. Apparent temperature can be read from a chart of ambient temperature versus relative humidity. Changes in windspeed or in amounts of direct radiation (insolation or terrestrial and sky radiation) can be factored in. However, he found that the effects of changes of windspeed in the summer are slight. The effect of barometric pressure was found to be negligible. He related apparent temperature to heat syndromes such as heat stroke and heat exhaustion. He did not discuss the relationship of apparent temperature to

illness or death from other diseases that might be brought about by heat stress. However, presumably the index should be a means for warning that people with chronic disease and the elderly might be at high risk and should take precautions to reduce exposure and limit physical activity.

Thus, heat wave studies point out that abrupt increases in temperature can accelerate death in many people; however, there are many uncertainties about the influence of variables other than temperature. Is the higher death rate in inner cities wholly due to higher temperatures in those areas, or do socioeconomic factors have a large influence? What influence does the underlying climate have? That is, if one climate is normally hotter than another, are people in the hotter climate better acclimated and thereby appreciably less vulnerable to sudden increases in temperature than those in a cooler climate? How much do such variables as humidity and air movement influence the extent of morbidity and mortality? How much influence does the rate of heat buildup within a season have? With the exception of the inner city and the socioeconomic questions, all these questions are pertinent to climate and related weather changes. That is, how much will regional and seasonal temperature, humidity, and air movement differ in a CO₂-induced climate change? However, perhaps the most important question is whether the variability in weather will increase or decrease; thus, whether the frequency of abrupt changes in temperature will change.

7.5 SPORADIC AND EXTREME WEATHER EVENTS

There are other sporadic, extreme weather events in addition to heat waves, whose frequency and intensity may change with climate change.

Droughts affect human health principally by the failure of crops and forage, consequently affecting nutrition and economics. Failure to obtain adequate nutrition, either because nutritionally adequate foods are in short supply or are too expensive, increases susceptibility to disease and early death.

Floods also may disturb nutritional status by destroying crops. In addition, in many cases homes are lost, leaving people exposed to the elements or crowded into temporary shelter. These situations increase the likelihood of disease and epidemics. Floods may contaminate water supplies, adding to the possibility of an increase in the occurrence of disease.

Tornadoes and hurricanes may kill and maim people, as well as destroy crops and housing, and may also increase the probability of the spread of disease.

To some extent, droughts are covered in Chapter 4 (this volume) and are referred to in this chapter with respect to the relationship of nutrition to disease. However, the effects of floods, tornadoes, and hurricanes depend strictly on the force of the individual events, the physical damage done, and the area affected. There is no way to quantify their effects or predict their frequency under a CO₂-induced climate change at this time. When there is more information about regional and seasonal climate change, it may be possible to predict the probability of an increase or a decrease in frequency of these extreme events in a particular region.

7.6 AIRBORNE MATERIALS RELATED TO HUMAN HEALTH

Many airborne bacteria, viruses, fungi, and allergens that cause human illnesses are distributed in the atmosphere. Atmospheric conditions, especially temperature, precipitation, humidity, and wind, will affect the multiplication, dispersal, and survival of these organisms. Thus, a CO₂-induced climate change may affect their prevalence.

The bacteria and viruses causing human diseases can become airborne through direct dispersal such as coughing and sneezing. They may also be disseminated on dry skin particles, from bedding, and so on. The majority of human diseases from airborne infectious materials are transmitted indoors, where there is close contact among people. Meteorological variables are related to this only to the extent that they influence the indoor environment by effects on air temperature and humidity. However, infectious materials may also become airborne outdoors by the injection of materials in the air by, for example, water cooling towers, sprinkler irrigation systems, spray from waves, raindrop splashes, and industrial processes (especially those involving animals and animal byproducts). Although few measurements of the numbers and types of organisms injected directly into the atmosphere from rural locations have been done, it has been conjectured that harrowing operations, movement of large herds of animals over dry terrain, and other farm practices may contribute to rural loading of the atmosphere. Dust at high humidity can serve as a site for bacterial survival or can serve as a resting place from which such organisms as bacteria and viruses can be redispersed by the splash of raindrops or by vigorous air movement (Lidwell 1964; Akers et al. 1979).

The transport of biological materials suspended in air is the same for other materials of comparable size. Dispersal is dependent on atmospheric turbulence. Both horizontal and vertical eddies are involved. Turbulence

intensity depends on the roughness of terrain, the change of wind speed with height (wind shear), and the vertical temperature profile of the atmosphere. Insolation and wind speed principally determine the temperature profile near the surface. The amount of insolation determines the thermal turbulence, and the wind speed modifies the intensity of the turbulence. The dispersive ability of the atmosphere depends on whether it is unstable or stable, that is, whether forces acting on it enhance or reinforce its vertical motion (unstable) or suppress its motion and restore it to its initial position (stable). The unstable atmosphere increases dispersive ability; a stable (still) atmosphere allows buildup of pollutants. The degree of stability depends on the rate of temperature change with height (Chatigny and Dimmick 1979).

7.6.1 Bacteria

Bacteria survive outdoors in appreciable numbers for variable periods of time, and they are found fairly high in the atmosphere. For example, Fulton (1966) found as many as 200 microorganisms/m³ at an altitude of 3127 m. However, it appears that no major bacterial epidemics in humans are propagated by spread in the atmosphere. The survival of bacteria in the atmosphere is a function of many variables, including temperature, relative humidity, ultraviolet radiation, air pollutants, and the media in which bacteria are dispersed. Air temperature does not appear to be the usual limiting factor because most organisms can live at extreme temperatures (between -20° and 48°C); however, the effect of temperature is modified by relative humidity. The lethal effects of ultraviolet radiation are well known, but high relative humidity may protect some bacteria from these effects. Sampling and plating have been a problem in determining survival of airborne bacteria, and there is still much work to be done before the meteorological conditions involved can be quantified (Akers et al. 1979). However, a few examples related to airborne bacteria are summarized next.

Hyslop (1978) aerosolized various bacteria to test their viability in air. Tests on a mycoplasma at various relative humidities showed that survival was shortest at 80% relative humidity. *Escherichia coli*, at 20°C and 63% relative humidity, survived less than 3 hours. At least 10% of two mycoplasma strains of human pulmonary origin survived for 5 hours at 28°C and 50% relative humidity. A significant amount of *Salmonella typhimurium* remained viable for 24 hours at 21°-28°C and 50% relative humidity (in shaded daylight or darkness).

Katzenelson and Teltch (1976) examined the bacterial quality of air in the vicinity of wastewater spray irrigation in Israel. Viable coliform bacteria were found

at a distance of 350 m, and *Salmonella* was found at a distance of 60 m downwind from the source.

Blanchard and Syzdek (1970) found that air bubbles breaking at an air-water interface contained bacteria concentrated from 10 to 1000 times over that of the suspension from which they originated.

Wellock (1960) described a minor epidemic of Q fever (an influenza-like disease caused by airborne rickettsia [*Coxiella burnetii*]) in an urban area of the San Francisco Bay area. This disease is usually transmitted to humans from animals and animal products, and in rural areas the majority of cases are found in people who are in close contact with animals. Dust from lambing pens is often the source. The source of this particular outbreak was apparently a slaughterhouse and the fumes from a fat-rendering process. Cases were found in a fan-shaped, 10-block area downwind from the plant, and there was evidence that airborne dissemination occurred up to 16 km from the source.

Swedish scientists investigated a "red" snow that fell in February 1969 (Bovallius et al. 1978). It had from 70 to 120 bacteria/ml (*Bacillus* sp.), depending on where it was sampled. Snow that fell before and after the red snow had a count of only 1–4 bacteria/ml. At the time the snow fell, there was a stable high-pressure system over Russia and a low-pressure system west of Scandinavia, with a strong southerly air flow between them. The air transport route was traced, and the airborne material was found to originate in an area north of the Black Sea, where there were sandstorms at that time. Other investigators found pollen and minerals in the snow that were also compatible with those originating in the Black Sea. The authors did not state whether the bacteria were pathogenic.

Thus, bacteria are present in the atmosphere and may contribute to the spread of diseases over long distances but are not as effective in causing diseases as are bacteria found in high concentrations in indoor environments. This is probably due to factors in the outdoor atmosphere (e.g., ultraviolet light, air pollutants) that kill the bacteria, as well as the great dilution caused by air turbulence.

7.6.2 Viruses

Viruses in nature generally only multiply in living organisms and are usually transmitted to humans by close contact. As with bacteria, laboratory studies have been performed to find the type of environment in which they can survive. For example, Hyslop (1978) reported that poliomyelitis and other viruses tested showed progressively decreasing resistance to desiccation after aerosolization; poliovirus longevity in air was sufficient to permit dissemination across distances of several

miles; relative humidity, altitude, and solar radiation are among some of the principal determinants of virus survival; other meteorological factors may modify these influences.

Falk and Hunt (1980) state that airborne viruses are associated with two types of particles, that is, droplet nuclei (propagated from sneezes, coughs, etc.) and dust particles (shed from skin and clothing) and that the dust particles are associated with localized epidemics. Harper (1963) aerosolized poliovirus and vaccinia virus at 20, 50, and 80% relative humidity. The poliovirus survived best at 80% relative humidity, but the vaccinia virus survived best at 20% relative humidity. Rechsteiner (1970) found, for respiratory syncytial virus, high infectivity at high relative humidities and low infectivity at low relative humidities.

Several viral diseases of animals have been shown to cause epidemics at some distance from the source, and the viruses were almost certainly airborne. By implication, this could happen in human diseases, but atmospheric (outdoor) spread of human pathogenic viruses has not been shown to be a factor in major epidemics. Indoor airborne spread of viral disease has been implicated in epidemics, and indoor humidity and temperature are related to the viability of viruses. Although indoor environments are influenced by climate and weather, each microenvironment will be different, depending on ventilation, humidity, temperature control, and so forth.

7.6.3 Fungi

Fungal lung infections are relatively common occurrences in certain areas of the United States. It has been estimated (Furcolow 1965) that annually 500,000 people acquire histoplasmosis (caused by the fungus *Histoplasma capsulatum*), and that about one-third of them develop a clinical illness that ranges from a very mild respiratory disorder to a serious and frequently fatal condition in which the fungus spreads to other areas of the body. Possibly 90% recover without chemotherapy or hospitalization, and many cases are misdiagnosed as viral diseases. It is not required that this disease be reported to public health officials; therefore reliable statistics on its occurrence are not available. However, this disease, along with other fungal diseases, probably accounts for much time lost from work and school (Hasenclever 1979). The different fungi responsible for these infections apparently require different climatic conditions for survival and dispersion.

Furcolow and Horr (1956), in investigating *Histoplasma capsulatum*, found prevalence of this fungus in an area of the United States (Midcentral and Mideastern States) where annual precipitation is 76

to 127 cm and the average summer temperature is between 21° and 27°C. They think that the direction of the prevailing winds tends to limit the fungus to this area. However, Hasenclever (1979) believes that it is distributed worldwide in temperate, subtropical, and tropical regions, but that there are foci where the microclimate is ideal for rapid multiplication of the fungus and that when these foci are disturbed (digging, plowing, etc.), epidemics occur in areas downwind.

Coccidioides immitis, another soil fungus, is common in certain areas of the Southwest and parts of California. Maddy (1957) investigated the areas where the fungus was most prevalent and related climatic factors to this prevalence. The fungus apparently thrives in climates where summer temperatures are hot enough to sterilize the surface soil, thereby eliminating competing plants (July ambient air temperatures from 26° to about 32°C), and where there is very little freezing at ground level (January ambient air temperatures range from about 4° to 12°C). Rainfall is also an important factor, with 13–50 cm being ideal. Temperature and rainfall outside these ranges are less favorable for the fungus. Hugenholtz (1957) also found that winds that raise dust storms, mainly in the spring and fall (especially after a period of precipitation), increase the incidence of infection.

Climate changes could either extend or limit the areas in which these fungi are prevalent and responsible for widespread respiratory disease. Separate studies would be needed for each fungus to determine its survival under new climatic conditions.

7.6.4 Pollen

Pollen from plants are found worldwide and are one of the most common causes of allergies in humans. Pollen grains are minute and are thus easily airborne and dispersed over long distances. Meteorological conditions may limit or expand their dispersal and, in some cases, their production.

Hay fever afflicts approximately 6% of the U.S. population, being most prevalent among the 25- to 44-year age group. The economic impact of the work loss of so large a fraction of the work force is substantial, the discomfort is great, and many of the cases may develop into asthma. Ragweed pollen is one of the most common causes of hay fever. Most of the eastern two-thirds of the United States is exposed to the pollen of this plant (Dingle 1964). Because ragweed grows best in cultivated land, it is largely a product of farming practices. Weather is a determining factor in the aeroallergen problem. Rain, wind, and humidity affect the dispersal of the pollen in the air and thus modify the extent of human exposure to pollen and the severity of the hay fever. The

pollen season for ragweed is August–September. The crop is dependent on rainfall in June, July, and August. Drought will delay the onset of the pollen season. As in agriculture precipitation, temperature, and soil moisture are important. In Michigan, for example, high May rainfall and low July rainfall will produce a maximum yield of ragweed pollen.

7.7. SEASONAL DISEASES CAUSED BY MICROORGANISMS

7.7.1 Airborne Diseases

Many infectious diseases are transmitted from human to human by the airborne route. Most respiratory diseases are more prevalent in cold or changeable weather than in warm weather. The reasons for this climatic influence are debatable. Ford (1981) offers the following as possible reasons: (1) a positive effect of cold weather on the survival of the causative pathogens; (2) the depression of the immune system at lower temperatures; (3) increased opportunities for transmission as people are confined indoors (with higher concentrations of infectious agents) for longer periods; and (4) lack of vitamin C because of the reduced availability of fresh vegetables. It has also been suggested that the drying out of the mucous membranes, from low humidity in heated environments, may be partially responsible for the seasonality of these diseases.

Influenza epidemics occur in the winter in both the Northern and Southern Hemispheres and, although the climate relationships to the rather abrupt appearance of new and virulent strains have been sought, it has not been found (Hope-Simpson 1979). However, Tromp (1980) stated that influenza virus and gram-positive bacteria (including pneumonia-causing bacteria) die more rapidly with high humidity and vigorous air movement. Thus, the winter months with very low humidities and little air movement in centrally heated buildings are favorable for the transmission of infectious respiratory diseases.

The occurrence of epidemic cerebral meningitis, a winter disease, has been correlated with the influx of warm, humid air masses (Tromp 1963).

Streptococcal infections and diphtheria are more prevalent in the autumn and early winter, but meteorological influences have not been determined.

Poliomyelitis is more prevalent in the summer (Tromp 1963, 1980). There is evidence from studies carried out in the United States that the incidence of this disease is related to relative humidity; that is, it occurs when the relative humidity rises above about 28% (Armstrong 1952). In the tropics, the maximum incidence is during the rainy season.

In most cases, the precise relationships of meteorological variables to the incidence of these diseases are unknown, although trends may be fairly well established. With CO₂-induced global warming, it would generally be assumed that summer diseases would increase and winter diseases would decrease. However, other meteorological variables, for example, humidity and rainfall, also influence the prevalence of these diseases. CO₂-induced changes in these meteorological parameters, on a regional and seasonal basis, are currently uncertain. Thus, the effects of a CO₂-induced climate change on the prevalence of these diseases are also uncertain.

7.7.2 Human Carrier Diseases

Communicable diseases, which are not usually transmitted by air, are influenced by climate and weather conditions. These diseases are usually transmitted by contact (e.g., hands touching food) and by water contaminated with urine or fecal matter. A few examples of the relationship of climate to these diseases follow.

Cholera is a disease that is prevalent in the summer. It is transmitted by the fecal contamination of water, but there is recent evidence that the organism can be found in water not fecally contaminated. It becomes dormant when water is cold and multiplies rapidly when the water warms. May (1958) defined the summer isotherms for cholera as approximately 15°–27°C (average temperature for the hottest months). Rainfall and humidity also have been implicated in influencing the incidence of cholera.

The group of *Salmonella* organisms (causative agents of typhoid, paratyphoid, and other intestinal diseases) are usually transmitted by contaminated water and food. These bacteria survive longer when the weather is cold than when it is hot (May 1958), and at thawing time there may be invasions of lakes and streams by bacteria-contaminated materials.

Bacillary dysentery is prevalent in temperate countries during warm, moist months and in subtropical and tropical countries during the rainy season (Sangster 1977).

Each of these diseases needs to be examined individually, and regional and seasonal climate changes must be known in order to define the effects of a CO₂-induced climate change.

7.7.3 Vector-Borne Viral and Bacterial Diseases

In vector-borne viral and bacterial diseases it is usually climate and weather influences on the vector or the vector's intermediate host, rather than the microorganism, that determine the prevalence of disease.

Although large epidemics of plague have not occurred in recent years, it is endemic in many parts of the world including the Southwestern and Western States in the United States. The disease usually is transmitted from rodents to humans by flea bites. Plague epidemics have occurred when temperatures have been about 19°–26°C with high relative humidity; for example, during the plague epidemic in Brazil, the relative humidity was between 66 and 83% (Pollitzer 1954). When the temperature increases above about 26°C, the incidence of plague decreases, apparently because fleas are susceptible to desiccation. A study conducted in Vietnam (Olson 1969) showed that the incidence of plague was inversely related to the amount of rainfall. For unknown reasons, as the amount of rainfall increases, the flea population decreases; it is speculated that the flea drowns or gets caught in the mud in rat holes.

There are several different strains of viruses that cause encephalitis and are transmitted to humans by the culicine mosquito. Birds are a reservoir for the virus. The virus strain and the species of the carrier mosquito determine the prevalence of the disease. There are periodic outbreaks of encephalitis in the United States and many other countries. Rainfall (Burnet 1952) and temperature (Hess et al. 1963) are factors in the epidemics. Rainfall and flooding provide breeding ponds for mosquitoes. Incubation periods for the virus in the mosquitoes are much longer at 20° than at 32°C. Thus, as the temperature increases, when the viruses and mosquitoes are present, the probability of epidemics becomes greater. At least one mosquito vector stops biting when the temperature drops below 15°C.

The prevalence of these two diseases would be affected differently by climate change, depending on the combination of meteorological variables. Plague would probably be less prevalent if the temperature increased above about 26°C with low humidity; although large amounts of rainfall might also decrease the prevalence. On the other hand, encephalitis would be expected to increase with an increase in temperature and rainfall.

7.7.4 Parasitic Diseases

Parasitic diseases are currently more prevalent in tropical and subtropical climates than in temperate climates, although some are a problem in temperate areas. Technology, improved sanitary conditions, and the education of the populace assist the control of vectors and parasites. However, there is a large climate influence that contributes to the prevalence of these diseases in the warmer and sometimes more humid areas of the world. Chronic infections with parasites frequently contribute

to malnutrition, decreased work ability, and greater susceptibility to other diseases.

7.7.4.1 *Vector-Borne Parasites*

Malaria is still one of the world's largest health problems, despite the fact that it has been controlled in many areas of the world by changes in agriculture and by mosquito abatement programs. There are still many areas where malaria is endemic and where epidemics occasionally occur. In hyperendemic regions (where 75% of the children have enlarged spleens) there is high childhood morbidity and mortality, high immunity in adults, high abortion rates, and low birth rates (Learmonth 1977). In epidemics there is high mortality and morbidity at all ages (although children and the aged are most at risk); there is a temporary increase in abortions, and a reduction in conceptions and birth rates. The plasmodia (parasite) develops in *Anopheles* mosquitoes and is transmitted to humans by the mosquito bite. There are some 50 species of *Anopheles* that are important vectors. One of the problems in controlling mosquitoes is that different species have different susceptibilities to the chemicals used for control, and each has a different ecological niche. For example, some like brackish water, some like clear water, some like sunlit water, some like still water, and others like fast-running water. Thus, an increase or decrease in rainfall may modify the habitats to the advantage of some species and to the disadvantage of others. A crude generalization (Learmonth 1977) regarding temperature and humidity is that mosquitoes breed and are active at temperatures above 16°C, and a relative humidity of about 60% is ideal. Temperatures in excess of about 35°C and average relative humidity of less than 25% will cause either death or dormancy. Also, the rate of development of the parasite (sporogony) in the mosquito depends on temperature; for example, for *P. falciparum*, it takes 9 days at 30°C, 11 days at 24°C, and 20 days at 20°C (Garnham, 1964).

Other vectors of parasites and the parasites they transmit require somewhat different climatic conditions.

7.7.4.2 *Parasites Requiring Intermediate Hosts*

There was an estimate of about 200 million cases, worldwide, of schistosomiasis in 1975 (Markell and Voge 1981). The life cycle of the parasite is spent partly in humans, partly in water, and partly in snails living in still or slow-moving water contaminated by human urine or fecal material. There are several species of schistosomes and the snails that carry them. The parasite enters humans by penetrating the skin when the human comes in contact with schistosome-contaminated water. They then may cause pulmonary, hepatic, intestinal, urinary, or central nervous system problems. Environmental factors, which influence the prevalence of the disease,

act on the water phase of the parasite and on the snail host. Temperature influences various stages of the cycle. Below about 9°C snails are not usually infected by the parasite. When the temperature rises above about 35°–39°C the snails die. The temperature most favorable for the water/snail cycle of the parasite is 26°–28°C (Kendall 1964; Purnell 1966; Anderson and May 1979). Heavy rainfall can wash the snails from their ecological niches, but, generally, rain is advantageous for snails because it keeps their areas wet enough for survival. The snail population usually peaks during the season of high rainfall (Anderson and May 1979). Unfortunately, artificial water resources such as dams, irrigation canals, and water impoundments (built for health and economic reasons) are ideal breeding and living areas for the schistosomes during the water and snail phases of the life cycle. Despite attempts to control it, schistosomiasis continues to spread worldwide (Heyneman 1982). It is also frequently carried to new areas by migrants, some of whom are escaping from drought-stricken areas. Thus, changes in climate may influence the spread of this parasite in many ways. Whether a climate change is advantageous or disadvantageous to the parasite and its host will depend on the direction of regional and seasonal changes, in particular, changes in temperature and precipitation. Health education of the population in areas contaminated with the parasite could also influence its prevalence.

7.7.4.3 *Parasites That Do Not Need Intermediate Hosts or Vectors*

The hookworm, endemic in parts of the United States, is an example of this type of parasite. In 1975 the hookworm was estimated to infect about 450 million people worldwide. The eggs are passed from the human feces to soil where, with favorable conditions, they hatch, and the larvae develop and transform to the infective stage. Given the opportunity, they then penetrate human skin. They may cause diarrhea, anemia, and occasionally pneumonitis, if the infecting dose is large. They are generally confined to those parts of the Northern Hemisphere south of the 36th parallel, and north of the 30th parallel in the Southern Hemisphere (Markell and Voge 1981). Eggs and larvae are subject to freezing and desiccation and are very sensitive to climate. The optimal temperature for eggs to hatch is from 27° to 32°C, and they need at least 127 cm of rain per year (Gilles 1984).

For the diseases briefly described above, as well as a number of other parasitic diseases, CO₂-induced increases in temperature may provide new geographic areas suitable for the survival and multiplication of vectors or intermediate hosts. In addition, current endemic areas may be modified so that there are more

or fewer life cycles of parasites or vectors during a year. Changes in rainfall could also affect the prevalence of parasites by affecting breeding sites of vectors or hosts. If migration of humans and new water projects are a consequence of CO₂-induced climate changes, the control of these diseases may become greatly complicated.

7.8 NUTRITION

7.8.1 Climate and Weather Effects on Agriculture

Much of the world's population, particularly in the developing countries, is either undernourished (low caloric intake) or malnourished (lacking essential nutrients). This may result in retardation of growth and development beginning in the fetus and continuing throughout childhood and adolescence. Many humans whose caloric intake is adequate are malnourished because the predominant foods are from plant sources that lack or are low in essential nutrients, such as proteins, or have the nutrients (e.g., iron) in such chemical form that they are not easily absorbed. Although these problems are being addressed both on a local and worldwide basis, they are far from being solved (Newman 1975a).

Agriculture, both plant and animal, will be affected by climate changes. Whether these changes are beneficial or detrimental will depend on the extent and type of regional and seasonal changes. For plants, either the amount of crop production or the type of plant that will grow efficiently may change. Both domestic and aquatic animals may be affected. If in a particular region the amount of food production declines or production is switched to foods that are not as balanced nutritionally, then the nutrition of the regional population may suffer (see Chapters 4 and 5 of this volume for more discussion of the effects of climate change).

In addition to changes in food production, society's need for nutritional energy may increase under a CO₂-induced warming. It has been demonstrated by Consolazio et al. (1961) that more calories are needed for a heavy work load in ambient temperatures over 30°C (86°F) than are needed at lower temperatures.

7.8.2 Interactions of Disease and Nutrition

There are also interactions between infectious and parasitic diseases and nutritional deficiencies. Nutritional status can influence both susceptibility to disease and the outcome of disease. The disease may also alter the nutritional status of the person affected (Scrimshaw et

al. 1968; Mata et al. 1972). The effects of a CO₂-induced climate change on nutrition and disease prevalence may either help a particular situation or make it worse, depending on regional and seasonal changes and their effects on the diseases and on food production.

7.9 WATER

Water is essential to all forms of life, including that of humans. Precipitation is variable both seasonally and regionally. Regional changes in the amount and timing of precipitation, temperature, humidity, and wind influence the amount and quality of fresh water available for humans, thereby affecting the quality of life. See Callaway and Currie, Chapter 3 of this volume, for a discussion of the effects of climate change on water resources.

7.9.1 Quantity of Water

The quality and quantity of nutrition is very dependent on the amounts of precipitation in a region because of the dependence of agriculture (both plant and animal) on water resources. In addition to the total amount of precipitation, agriculture is dependent on the regional and seasonal timing of this precipitation. At opposite ends of the precipitation spectrum, droughts and floods can adversely affect the agriculture of a region. In some areas of the world, the products of fisheries are vital sources of protein, and the fisheries may be affected by the amounts of organic matter carried by runoff from precipitation (see Chapters 4 and 5 of this volume for more details).

Forests and other nonmanaged vegetation are dependent on precipitation in much the same way as agriculture. Many forest products are needed for maintaining or improving the quality of human health; for example, shelters are vital for alleviating stress on the thermoregulation mechanisms and are helpful in protecting humans from harmful elements of the environment (see Chapter 6 of this volume for details of climate effects on forests).

The availability of water, which is essential for drinking, cooking, sanitation, and so forth is dependent on precipitation for groundwater recharging, as well as for maintaining streamflow and filling lakes and reservoirs. When these resources are not adequately replenished, human health and life are endangered.

7.9.2 Quality of Water

The quality of water is dependent largely on the quantity of precipitation. Groundwater, which has percolated

through soil and rock and has had impurities filtered out, is usually the purest water for drinking, cooking, and sanitation. Frequently groundwater also has essential trace elements added as it moves through soil and rock. When there is insufficient precipitation to replace the amounts withdrawn, and groundwater is depleted, less pure water from streams, lakes, and reservoirs will be used. These sources also are dependent on precipitation for replenishment and for the dilution of impurities accumulated from biological or industrial sources. In developed nations, surface water usually goes through purification processes before human use, but these processes do not always remove all noxious materials. In developing nations, frequently the water used for drinking, bathing, and so forth is taken directly from the surface sources, which may be highly contaminated with harmful materials (biological and chemical), and the amount of precipitation in these localities will largely determine the concentration of these materials. If there is fast-flowing water, the material may be diluted or washed out. Stagnant water, sometimes created by rain collecting in depressions or by flooding, is an ideal environment for many pathogenic organisms. In some cases groundwater wells may be contaminated by biological materials when rains are heavy and runoff flows into them. Cultural and sanitation practices as well as poverty contribute to the problems created by the use of impure water.

If water becomes scarce in a particular region or if there is too much or poorly timed precipitation, there may be adverse effects on human health. Conversely, if areas that are now deficient in precipitation receive more precipitation, or if areas that now get too much seasonal water receive precipitation more evenly over the seasons, then the effects of climate change may be beneficial to those areas. The rate of change in precipitation will also be important; that is, if precipitation declines in a region and does so slowly, there may be time for adaptive measures such as construction of reservoirs, modification of methods of irrigation, and development of plants that are more drought tolerant. The effects of a CO₂-induced climate change on water resources will depend on regional and seasonal changes, which are currently uncertain.

7.10 SHELTER

Shelter is one of the ways in which humans protect themselves from extremes in temperature. Well-planned residences in tropical climates are built for maximum ventilation; whereas those in extremely cold climates are built for maximum insulation, and those in temperate climates are built such that they can be open in summer and closed and insulated in winter. Unfortunately, there

are many residences and work places that are not well planned. In particular, the inner cities in many areas are built such that they absorb and retain heat. These are the so-called heat islands. This situation has been highlighted in several studies of heat waves (see Section 7.4.2) where there was a higher percentage of deaths in the midcity than in the suburban and rural areas (Henschel et al. 1969; Clarke 1972b).

CO₂-induced warming of the Earth, particularly if there should be more heat waves (which will depend on currently unknown changes in the variability of weather), may make this situation more acute. The planning of cities and revisions of building codes should take this situation into consideration to avoid or alleviate heat absorption and retention (World Meteorological Organization 1970a, 1970b). Meteorologists should be intimately involved in the planning. This is a situation that currently needs attention, regardless of the potential for CO₂-induced climate change.

7.11 AIR POLLUTION

A CO₂-induced climate change, in itself, will not add noxious air pollutants to the atmosphere. However, changes in local weather due to a change in climate may affect the concentration of air pollutants either by dispersing them more rapidly or by allowing concentrations to accumulate. Air pollutants that are harmful to human health usually are generated and are more concentrated in the atmosphere of industrial and metropolitan areas. Generally, areas most in danger from health-threatening pollutants are those in low-lying areas, that is, basins in hilly or mountainous areas or river valleys that are somewhat protected from the wind. However, if the meteorological factors are unfavorable, life-threatening episodes can occur in other types of terrain. In several acute episodes of air pollution where excess deaths occurred, there was fog combined with high pressure systems (Prindle 1964), which held the smoke and other air pollutants near the ground.

The effects of CO₂-induced climate changes on the occurrence of acute air pollution episodes in a region will depend on the seasonal changes in meteorological variables in that region. If these changes cause air pollutants to disperse more quickly than occurs in the current climate, then the change should be beneficial. If the changes are conducive to the buildup of air pollutants, then they will be detrimental.

7.12 RECREATION

There are many possibilities for changes in outdoor recreation and tourist areas if there are changes in climate. If the climate is hotter and precipitation does

not increase, such things as low lake and low river levels will occur. Alternatively, if precipitation does increase in some areas, there may be improved conditions for water-related recreation. Forest areas, including national and local parks and snow areas for winter sports, may also change. The effects of a CO₂-induced climate change in these examples and in other recreation and tourist areas will depend on regional and seasonal changes in climate, which, however, are currently uncertain.

7.13 SUMMARY AND DATA AND RESEARCH NEEDS

A number of aspects of human health that are related to climate and weather variables may be affected by climate change. These include the relationship of climate and weather variables to the mortality rate from diseases such as heart, cerebrovascular and respiratory; birth defects and fetal and infant mortality; survival and geographic prevalence of disease-causing organisms such as bacteria, viruses, fungi, pollen, and parasites (and their vectors and hosts); nutrition; and shelter needs. Often research has been (and is being) performed to determine more precisely the relationship of meteorological variables to human health. For example, the knowledge gained in this research is being used in many cases in the control of parasites. There is, however, much more to learn about these relationships and how they may be used to improve human health. In addition, there are areas of the world where current knowledge and technological advances are not being used as efficiently as is possible because of factors such as lack of education, lack of funds, and cultural practices. In some of these situations, climate change may intensify the problems, in others it may be beneficial. In many human health situations, even if CO₂-induced regional and seasonal climate changes were known, the background information needed to predict effects of these changes is unknown or uncertain. However, at least some of this background information is obtainable by defining and comparing the relationships of meteorological variables to health and mortality in current, but differing climates. Table 7.4 tabulates knowns and uncertainties regarding the climate relationship to human health. Data and research needs are discussed next.

7.13.1 Climate Data Needs

Many aspects of human health and welfare are affected by meteorological variables. To specify qualitatively and quantitatively the effects of a CO₂-induced climate change on human health, it is necessary to know the rate at which climate change will occur, regional and seasonal climate changes, and changes in the variability

of weather. The state of current climate research is such that it is not possible to predict this information with any certainty. Until such time as definitive regional and seasonal changes are predictable, it would be useful to have an estimate of the limits of climate change, that is, the range of probable change in meteorological variables for regional health effect studies. For the climate needs of water resources, agriculture, fisheries, and forests related to human health, see Chapters 3, 4, 5 and 6 of this volume.

7.13.2 Carbon Cycle Data Needs

The CO₂ fertilization of plants, which is related to agriculture and thereby to human nutrition, is being studied separately. The data needs from studies of the carbon cycle will be found in the report on vegetation effects (Strain and Cure 1985).

The direct effects of breathing increased levels of CO₂ on human health have been addressed elsewhere (U.S. DOE 1982; Bland et al. 1982), and on the basis of current knowledge, it appears that the effects will not be deleterious. However, should new information appear indicating a need to study further the direct effects of CO₂ on human health, information from carbon cycle research will be needed, including the rate at which the atmospheric CO₂ concentration will increase and the maximum expected concentration.

7.13.3 Medical and Biological Research

Determining the effects of a CO₂-induced climate change on human health, beneficial and detrimental, will depend on the magnitude of regional and seasonal changes in climate and changes in the variability of meteorological variables. Although the CO₂ Climate Program is making progress in this direction, apparently, it will be some time before this kind of information will be available. However, there are medical and biological fields in which work pertinent to the effects of climate change has been done or is in progress. This is due to current concern about the influence of climate/weather variables on human health. This research should be continued and intensified, by the agencies already involved, to obtain information that will not only be valuable currently, but that will be helpful when more is known about the directions of CO₂-induced regional and seasonal climate changes. The prospect of a CO₂-induced climate change adds some urgency to solving these problems and finding ways to ameliorate them. High-priority research related to meteorological influences is outlined next.

Table 7.4
Knowns and Uncertainties Regarding Principal Climate Effects on Human Health

Health Concerns	Climate Variables Involved	Knowns	Unknowns and Uncertainties
Organic Diseases and Heat and Cold Effects	Temperature Humidity Precipitation (including snow)	As temperature becomes progressively colder or excessively hot, mortality increases. All climate variables listed influence mortality to some extent. Older age groups are particularly vulnerable to the effects of extremes in meteorological variables or rapid changes in weather. Abrupt increases (heat waves) or decreases (cold snaps) in temperature markedly increase mortality in people with underlying organic disease. Increases in morbidity and occasionally mortality in people in apparently good health can result from extreme heat (heat stroke).	The extent to which meteorological variables influence the onset and progression of organic diseases is largely unknown. For example, does the onset of heart disease occur (on average) at an earlier age in one climate as compared with a different climate? Is a particular disease more prevalent in one type of climate than in another? Which variables are responsible and how do they interact?
	Wind persistence and speed Various weather types (fronts, etc.)	During heat waves the following variables influence the extent of mortality and morbidity: Maximum and minimum daily temperature Daily variations in temperature Length of the heat wave Sex, race, socioeconomic status, housing, physical activity, air-conditioning	When there is temperature stress, the extent of underlying climatic influence on age-adjusted mortality rates from various organic diseases is very uncertain, i.e., does mortality from a particular disease occur at earlier ages in one climate compared with another? When there is temperature stress, the extent of interaction of the various meteorological factors in contributing to mortality from various diseases is uncertain. For example, what influence do variations in humidity at a particular temperature have? The temperature (hot or cold) at which there are abrupt increases in mortality appears to differ with climate, but the influence of modifying meteorological factors is not completely resolved, nor are many of the nonclimatic regional factors that may influence mortality resolved. During heat waves, the relative contributions to <i>morbidity</i> and <i>mortality</i> of the following are uncertain: Maximum and minimum (night) temperature Variation in temperature Length of heat wave Pattern of preheat wave temperature buildup Effect of underlying climate, e.g., normal, nonheat wave temperature for the season Effect of acclimation due to earlier heat waves Influence of factors such as sex, race, socioeconomic status, housing, physical activity, air-conditioning, etc.

Table 7.4 (continued)

Health Concerns	Climate Variables Involved	Knowns	Unknowns and Uncertainties
Thermoregulation and Acclimation	Temperature	Initiated when body temperature moves outside normal range (cooler or warmer).	Frequent variations in ambient temperature or long-term residence in extreme climates may put appreciable demands on thermoregulatory systems. It is not known whether these demands are beneficial or whether they may eventually lead to diseases of, for example, the circulatory system. Effects on thermoregulatory and acclimation mechanisms of moving in and out of hot and cool areas (e.g., work and air-conditioned areas) is uncertain.
	Humidity	Many of the physiological and nervous system mechanisms of thermoregulation are known.	
	Wind speed	Ambient temperature, wind speed, and humidity tend to modify body heat content and through this, thermoregulation. Acclimation to abrupt change in climate essentially takes place in a few weeks in healthy individuals.	
Physiology and Biochemistry	Temperature Humidity	There are seasonal variations in physiological systems and biochemistry.	Reasons for these variations are somewhat uncertain, as is their relationship to morbidity and mortality
Conception and Birth Defects	Largely unknown	There are climate (seasonal) influences on the extent of adverse reproductive outcomes, e.g., stillbirths, malformations, mental disease.	The influence of season is small but significant; however, the influence of factors unrelated to climate is much larger, and these need to be specified before specific effects of meteorological factors can be determined.
Airborne Pathogens, Viruses, and Bacteria	Temperature Humidity Precipitation Wind speed	Most airborne pathogens are transmitted from person to person indoors, where humidity is probably the most important factor, both for survival of the organism and for infecting humans. Survival and dispersal outdoors is dependent on humidity, precipitation, wind speed and direction, ultraviolet radiations, and other nonclimatic factors.	Ranges of climatic conditions for the survival and spread of most pathogens outdoors are not well defined. Distances over which pathogens can be dispersed before being inactivated are uncertain. Reasons for disappearance and reappearance of many pathogenic diseases (e.g., influenza epidemics) are not known.
Pollen and Fungi	Temperature Humidity Precipitation Wind Seasonal difference in climate variables Timing of peak temperatures and precipitation	Temperature, humidity, and precipitation requirements of some pathogenic fungi are known. Timing of temperature and precipitation for the highest production of some pollens are relatively well known.	Climate variables needed for some pathogenic fungi to grow and to be dispersed. Reasons for variations in the extent of production and dispersal for some pollen. Precise relationships of airborne allergens to asthma.
Vectorborne microorganisms	Temperature Humidity Precipitation Wind speed and direction	The climatic conditions necessary for some vectors to thrive and for the microorganisms to multiply within the vector are known. Some microorganisms known to have alternate hosts, e.g., birds.	Ideal environmental conditions for the survival and multiplication of the microorganism in the vector are uncertain in some cases. The role of the alternate hosts, the ideal climate conditions for the host, and the multiplication of the microorganisms in the host are frequently not clearly resolved.

(continued)

Table 7.4 (continued)

Health Concerns	Climate Variables Involved	Knowns	Unknowns and Uncertainties
Disease transmitted by human contact or through fecal or urine contamination of food or water	Temperature Humidity Precipitation	Often it is known that ambient temperature and humidity are related to the survival of these disease organisms outside the body. Heavy rains may be responsible for dispersing these organisms into drinking and bathing water. Insects spread some of these diseases via their contaminated legs.	For many of the organisms the exact ambient conditions in which the organisms survive and may be transmitted is not known. These diseases are thought to be more virulent in areas in which there is under- or malnutrition, but interrelationships are not well specified.
Parasitic diseases	Temperature Humidity Precipitation Wind speed and direction	Environmental conditions required by some parasites, their vectors, or intermediate hosts are relatively well known, and the areas in which they are endemic are fairly precisely mapped.	For some parasites, their vectors, and intermediate hosts the environmental requirements or the areas in which they are endemic are not precisely defined. The areas into which these diseases move, on the basis of current climate, given appropriate circumstances (e.g., migration of vectors or carriers) is not completely determined in many cases.
Nutrition	Temperature Humidity Precipitation Wind Timing of peak temperature and precipitation	Failure of crops-under-production of agriculture, or lack of production of foods with essential nutrients will lead to mal- or undernutrition. Poverty, even though nutritious foods are available, will affect nutritional status. Some diseases interfere with nutrition. Under- or malnutrition may influence susceptibility to or progression of some diseases.	Regional and seasonal CO ₂ -induced climate change and the effects of increased ambient CO ₂ concentration on agriculture must be known before effects of increased CO ₂ on agriculture and thus on nutrition can be predicted. The interrelationships of disease and nutritional status are in many cases poorly understood.
Water quality and quantity	Temperature Humidity Precipitation	Water availability and its quality affect, in some way, almost all aspects of human health.	Information on regional and seasonal CO ₂ -induced climate change is required before predictions of the effects on water resources, and the consequent effects on human health, can be determined.
Shelter	Temperature Humidity Precipitation	Properly planned shelter can protect people from some of the adverse effects of meteorological variables.	The extent to which types of housing affect morbidity and mortality during extremes in temperature are not well defined. Research for innovative ways of heating and cooling new buildings and cities is progressing, but research with meteorological input is not being as actively pursued as is needed for older structures (both commercial and residential).
Air pollution	Stagnant weather conditions Precipitation Wind	Stagnant air will fail to disperse air pollutants in areas in which they are produced.	The effects of a CO ₂ -induced climate change on air pollution will depend on regional and seasonal changes. Until this information is available, no predictions can be made.
Recreational	All meteorological variables	Recreational areas are very dependent on climate for their usefulness and appeal, and they could be altered by climate change.	The beneficial or detrimental effects of a CO ₂ -induced climate change on recreational areas cannot be predicted until regional and seasonal information is available.

7.13.3.1 *Organic Diseases*

Meteorological variables influence mortality and, to a largely unknown extent, influence morbidity from a number of organic diseases, such as heart and cerebrovascular diseases. Research should continue in this field and should ideally include (1) the effects of all meteorological variables over the range found within a given climate, including the effects of interactions of the variables; (2) the effects of changes in the variability of meteorological factors; (3) the effects of the rate of change of meteorological variables; and (4) studies of whether prevalence of diseases differs with climate and, if so, the extent to which meteorologic variables are responsible. The data used in these studies should be adjusted for factors such as age of population, socioeconomic status, sex, race, type of housing, place of residence (urban, suburban, rural), air-conditioning, and the availability of central heating. Meteorologists should be an integral part of the team of public health officials (epidemiologists, biostatisticians, etc.) involved in planning and executing the studies.

Mortality data are relatively easy to obtain from public records; however, useful morbidity data are much more difficult to obtain. Therefore, cooperation of the medical profession will be required to determine the approximate time of the onset of the diseases and the age of the patient at that time. The meteorological factors influencing initiation and progression of the diseases are probably more important than those responsible for mortality from a disease already developed to a stage where acute stresses of many kinds (especially temperature extremes) cause death. This kind of information will probably be very difficult to obtain, but an alternative, which might produce surrogate information, is to relate to climate and compare between climates the percentage of the population who die of particular diseases within certain categories such as age and sex. This could determine whether particular climates are more or less conducive to the onset of diseases at earlier ages. However, there are factors other than meteorological that contribute to regional differences in death rate from these diseases. Some examples are different percentages among regions of a particular race, sex, age, socioeconomic class, or city dwellers. The contribution of these factors to the variance in death rates must be resolved before the influence of meteorological variables can be precisely determined.

7.13.3.2 *Thermoregulation and Acclimation*

Thermoregulation and acclimation are related to the organic diseases discussed above. There has been considerable research in this area, and much is known about the physiology of thermoregulation and acclimation; however, it appears uncertain whether a long residence

time in either a hot summer or cold winter climate causes cumulative stress on the physiological systems involved and if so, whether this may lead to the early onset of, for example, diseases of the circulatory system. There is also uncertainty about whether time spent in air-conditioned premises leads to the loss of acclimation. If this is the case, it may lead to vulnerability in situations where air-conditioning is, at least temporarily, unavailable (e.g., outdoors, or when there is a mechanical or power failure). Research to elucidate these uncertainties is needed.

7.13.3.3 *Birth Defects and Infant and Fetal Deaths*

The role of meteorological variables in adverse reproductive outcomes is uncertain and needs to be elucidated. However, the underlying causes (which have the major influence) are also generally unknown and need to be understood before the role of meteorological variables can be determined.

7.13.3.4 *Bacteria, Viruses, Parasites, and Allergens*

The meteorological factors involved in the survival and multiplication of various microorganisms that cause human diseases and the hosts and vectors of these microorganisms are in some cases reasonably well defined. In other cases, the geographic areas in which these diseases are endemic are reasonably well known, but the precise meteorological conditions in which they survive and thrive are uncertain. Mapping current areas of endemism and defining the meteorological variables, and other variables not currently well known, which limit the habitat (or allow it to expand), would currently assist in controlling diseases. In addition, this information would assist in predicting areas in which new health problems might arise or in which current health problems may be alleviated should there be a climate change for whatever reason. This would allow monitoring techniques to be put into place and preventive measures to be planned.

7.13.3.5 *Nutrition and Disease*

Many areas of the world currently are plagued with a combination of nutritional deficiencies and disease. These contributors to poor health reinforce one another. Climate change may be either beneficial or detrimental to this situation, depending on regional and seasonal changes. The current work of local, national, and international agencies aimed at determining the meteorological factors involved and alleviating these problems should be continued and, where possible, accelerated.

7.13.3.6 *Shelter and Workplace*

City planners, architects, and engineers need to work closely with meteorologists on research to design new structures and their surroundings (e.g., green areas) and to remodel old structures such that meteorological

factors are used to the best advantage. This is a current need that may become more critical, especially for cooling human habitats if global warming results from an increase in atmospheric CO₂.

7.13.3.7 Recreational and Vacation Areas

Until regional and seasonal CO₂-induced climate changes (or at least an estimate of the direction and ranges of these changes) are known, research regarding the effects on these areas probably would not be productive and is not recommended.

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8. THE INTEGRATION OF DATA AND RESEARCH NEEDS

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Table 8.1
Data Needs from CO₂ Direct Effects Programs

Climate Research Needs	
<i>Temperature:</i> Regional ^a changes in means and variances of distribution of daily temperature by month; temperature extremes (seasonal); interannual temperature changes	
<i>Precipitation:</i> Regional changes in the mean and variance of the distribution of daily precipitation by month and type (rain, snow, sleet)	
<i>Humidity^b:</i> Changes in regional and seasonal mean and variances in distribution of daily humidity by month	
<i>Winds:</i> Regional and seasonal changes in wind patterns (direction, force, persistence)	
<i>Storminess:</i> Changes in regional and seasonal occurrence and intensity of storms (combinations of wind and precipitation)	
<i>Rate of climate change</i>	
<i>Changes in variability of climatic elements:</i> Month to month, season to season, year to year—including changes in the frequency of atmospheric pressure changes and extreme events, such as hail, floods, droughts, hurricanes, tornados	
Vegetation Response Needs	
Differential species response to increased CO ₂ (i.e., effects of fertilization and increased water-use efficiency) regionally for major crops, forest species, and native vegetation	
Interactions of Climate and Vegetation Response	
Regional and differential species changes due to the combined climate effects and vegetation response	
Carbon Cycle	
Rate of increase and eventual maximum concentration of CO ₂ in the atmosphere ^c .	
^a Regional denotes somewhat different areal dimensions for each of the fields studied. Within the fields there may also be differences (e.g., one specie's range may differ greatly from that of another). Examples of the ranges to be considered for the different disciplines are as follows:	
<i>Water Resources:</i>	Small drainage basins may cover only 10–20 km ² , the large river basins can cover thousands km ² .
<i>Agriculture:</i>	Specialty crops such as vegetables and fruits (grown in areas where soil, climate, and topology are ideal) may be grown in very small areas possibly 20–100 km ² . Conversely, grain crops (e.g., wheat and corn) may cover several thousand km ² .
<i>Fisheries:</i>	The adult range for some species (e.g., tuna, salmon, whales) can be ocean-basin wide (thousands of km ²). However, 400–500 km ² may be average. Spawning areas are frequently as small as single bays, estuaries, or rivers (tens of km ²).
<i>Forests:</i>	Many stands of forests species may cover only 50 or 60 km ² , others have much larger ranges.
<i>Human Health:</i>	Studies of illness and mortality rates may be done in cities, counties, states, or countries. However, within the larger areas, there may be geographical differences that influence climate. Thus, regions in human health studies may include 10 km ² up to thousands of km ² .

^bHumidity will not appreciably affect fisheries.

^cNeeded for fisheries and human health only—effects on other disciplines are through the vegetation response.

The objective of this study was to (1) characterize and define the information needed from other CO₂ research programs and (2) within the fields where indirect effects may occur, determine the data and research (including improvements in data collecting and interpreting techniques and in modeling) needed to quantify the indirect effects of CO₂. Information on the carbon cycle, climate change, and vegetation response is currently inadequate for determining indirect effects with precision. Table 8.1 generally lists the needs from the other CO₂ research areas. The type of information needed in most cases is the same for all the fields studied, exceptions being listed in the footnotes to the table. Table 8.2 describes data needs more specifically and illustrates these needs by examples from the fields.

In particular, the requirements from the climate program are projections of (1) seasonal and regional¹ temperature changes on a much smaller geographic scale than that of the current models; (2) changes in other climate variables, the most important of which is precipitation; (3) the rate at which climate will change; and (4) the changes in the variability of climate, particularly as it pertains to regions and seasons. The variability of meteorological factors and the rate of climate change are particularly important for quantifying indirect effects. In many cases, it will be changes in the extremes of weather rather than mean values that will have the greatest effect. If, as a result of CO₂ increase, there is less variability in weather extremes, most issues within the fields studied probably will benefit; however, if there is more variability, the results probably will be detrimental, depending on the extent of the change and the climate variable in question. The rate of change of atmospheric CO₂ concentration and the resultant climate changes will affect the rate at which indirect effects occur and the efficiency of adaptive processes, such as physiological acclimation and the application of technological measures for offsetting consequences of detrimental effects. A slow, regular change will be easier to adapt to than an abrupt change.

¹The areal dimensions of a region for which climate data may be required will vary widely depending on the geographic locality of the indirect effect being studied. For example, (1) studies on water resources may be on the drainage basins of small streams covering a few hundred km², whereas studies of large river basins may require data for areas covering thousands of km²; (2) studies on specialty crops may require data for comparatively small areas, whereas those on major grain crops may require data for areas covering thousands of km²; and (3) studies of spawning areas for fisheries may require data for only a single bay or river mouth, whereas studies on some adult fishery species may require data for whole oceans in which the adults range. Studies of seasonal effects also may require climate information that is different from one study to another. If there are changes, for example, in the timing of spring or fall frosts or of precipitation, one crop may be affected more or less than another, depending on where each is in its growth or harvest cycle at the time of the meteorological event; thus a particular type of climate information for one crop may be needed for April, another for May.

From the research on vegetation response, information is needed on how CO₂-induced changes in fertilization and water-use efficiency affect the major crop species, forest species, and native vegetation. Effects on native vegetation may affect water resources and forestry. The interactive effects of CO₂-induced climate change and vegetation response also are very important for determining indirect effects.

In addition to the information required from other CO₂ research programs, each field studied either suffers from lack of available, pertinent data or refinements are needed in research techniques (e.g., improvements in methods of data collection and interpretation, modification of existing models, development of new models). Table 8.3 lists some of these needs.

This study was not explicitly oriented to the search for and the evaluation of factors that might modify the eventual consequences of CO₂-induced effects. However, acclimation (occurring passively in humans and animals) and adaptation (using technological solutions such as genetic improvements of crops and agricultural animals, improved irrigation techniques, and increased water storage facilities) obviously may, in some cases, ameliorate the consequences of some possibly detrimental CO₂-induced effects. However, these may be limited in effectiveness because (1) human and animal physiological acclimation, for example, may help to adapt to a changed climate, but if the change is too rapid or too great, it may be inadequate to prevent illness and (2) many adaptive processes will take years to accomplish; for example, it may take 10 years to develop new varieties of grain, 20 years to develop new varieties of forage, or 50 years to plan and build new water storage reservoirs. Table 8.4 lists some of the possibilities for modulating the consequences of detrimental indirect effects; however, it is by no means an exhaustive list, nor have these possibilities been evaluated for their scientific, technological, or economic feasibility. The list is presented here only to point out that it may be possible to modulate some of the consequences of increased CO₂.

Institutional, social, and economic factors also may influence the consequence of indirect effects. Some examples of possible institutional influences are changes in national farm policy, changes in national and international regulation of fisheries, and changes in public health care services. Possible social influences include changes in demographic characteristics of regions and changes in regional land use; examples of economic influences are possible changes in the cost of water and the prices of farm, forestry, and fishery products. Changes in these factors either may ameliorate or make more detrimental the consequences of the indirect effects of increasing CO₂. Changes are usually adopted in response to prevailing conditions rather than

in anticipation of future conditions. These types of influences have been recognized in this study but no specific recommendations for formulating new social or economic policies or encouraging new market forces are included in the report. The need for change of this type in response to CO₂-induced effects cannot be projected until those effects are defined more precisely.

Before indirect effects and subsequent societal and economic consequences can be quantified, progress must be made in all the research areas mentioned. The most important information is, of course, quantitative data

from research on the direct effects of increased levels of CO₂ and the interactive effects of climate change and vegetation response. Information from these programs is currently inadequate for determining indirect effects. Until such time as the extent of specific regional and seasonal changes becomes available, indications of whether particular indirect effects will be beneficial or detrimental may be obtained when some information on the direction and ranges (upper and lower limits) of direct effects, for seasons and within smaller geographic regions, becomes available.

Table 8.2
Issues Within Fields That Require Direct Effects Data to Resolve Indirect Effects of Increased CO₂

Data needed	Water Resources	Agriculture	Fisheries	Forests	Human Health
<i>Temperature Changes</i> Regional^a changes in means and variance of distribution of daily temperature by month; temperature extremes; interannual temperature changes	Surface water supply: through effects of changes in snowmelt and evapotranspiration on runoff Groundwater mining: through effects on temperature-sensitive components of recharge and withdrawals Conflicts in use: indirectly, through effects on surface and groundwater supplies and through effects on temperature-sensitive components of water use Water losses from storage systems: evaporation and advection Vegetation management: through effects on transpiration and natural range of plant communities Drought Flooding: through immediate effects on timing and amount of runoff and long-term effects on density and structure of vegetation canopy River sedimentation: through long-term effects on density and structure of vegetation canopy Salinity: through effects of evapotranspiration on soil and stream salinity concentrations	Crops: vegetative, flowering and grain (fruit, vegetable) maturing periods — spring and fall frosts; cumulative warmth during growing season; length of growing season Weedy pests — same as “crops” (above) Insects and plant and animal disease: survival; yearly number of life cycles; geographic distribution Agricultural animals: survival and production Soil erosion: excessive drying of exposed soils; alternative freezing and thawing	Ocean temperature: affects growth and development rate of all species Stability/turbulence: affects production and species composition of plankton (food for juvenile fish) Ice extent: affects survival, migration, feeding, predators, and competitors	Seeds: affects sprouting Seedlings, saplings and mature trees: affected by extreme temperatures and cumulative growing season warmth Senescence: affected by extreme temperature Plant succession: dominant species will be ones for which changed temperature is most appropriate Pathogens/pests: temperature in microclimate will partially determine survival, prevalence, and geographic distribution	Organic diseases: effects of length of persistence of extreme temperatures and acute temperature changes on illness and death Thermoregulation: extent of stress on cardiovascular, cerebrovascular, and respiratory systems Physiology and biochemistry: seasonal changes Conception and birth defects: seasonal changes in rate Airborne organisms causing respiratory diseases: effects on production Vector-borne microorganisms: effects on the organism and the vector Communicable diseases: effects on the survival and multiplication of the disease-causing organisms Parasitic diseases: effects on the parasite and, if vector-borne, the vector Nutrition: affected through effects on agriculture and fisheries Water quality and quantity: affected through effects on water resources Recreational areas: effects on usefulness

Table 8.2 (continued)

Data Needed	Water Resources	Agriculture	Fisheries	Forests	Human Health
<i>Precipitation Changes</i> Regional^a change in the mean and variance of the distribution of daily precipitation by month	Surface water supply: through effects on timing, amount, and variability of runoff Groundwater mining: supply affected through changes in recharge; demand influenced by changes in availability of surface water Conflicts in use: indirectly, through effects on surface and groundwater availability Vegetation management: through long-term effects on density and structure of vegetation canopy Drought: through changes in long-term persistence of precipitation Flooding: through effects on type, intensity, duration and timing of precipitation events River sedimentation: through effects on sheet and channel erosion and long-term effects of changes in local precipitation on density and structure of vegetation canopy Salinity: through changes in leaching, dilution, and runoff of soil salts and through changes in salinity concentrations in streamflow	Crops and forages: vegetative, flowering, and grain (fruit, vegetable) maturing need specific amounts at specific times; too much causes waterlogging of soils, flooding of fields, leaching of nutrients Weedy pests—same as “crops” (above) Range animals: type, timing, and amount of precipitation can affect animals through drinking water supply, animal health, and amount of forage Insects and diseases: amounts of moisture present in soils and mulch at particular stages of life cycle may affect survival, persistence, and geographic distribution	Oceans: near shore salinity and ice extent, stability, and currents may be affected by runoff from precipitation Estuaries: input of some organic matter also depends on runoff from precipitation	Seedlings: affected by frequency of precipitation, throughout the year, frequency of spring soaking precipitation, days when soil moisture below wilting point, frequency and intensity of droughts Saplings: affected by frequency of precipitation, flooding, days when soil moisture below wilting point Trees: affected by frequency of precipitation, days when soil moisture below wilting point, frequency and intensity of droughts, fire frequency and extent (partially dependent on dryness of forest environment) Diseases: influenced by frequency of precipitation, days when soil moisture below wilting point, fire frequency, ice storms	Organic disease/thermoregulation: precipitation may increase thermal stress Airborne pathogens, viruses and bacteria: precipitation may clear air of some of these organisms; raindrop splatter may disperse from soil to air Pollen and fungi: need precipitation at certain times of development; when airborne, precipitation may clear from air Parasitic diseases and vector-borne microorganisms: some of the vectors need aqueous medium for breeding and living sites; some parasites live and are transmitted to humans in aqueous medium; heavy precipitation will sometimes flush organisms out of their aqueous medium and thus be beneficial

(continued)

Table 8.2 (continued)

Data Needed	Water Resources	Agriculture	Fisheries	Forests	Human Health
<i>Humidity Changes</i> Regional^a and seasonal mean and variance of distribution of daily humidity by month	Water losses from storage systems: humidity influences water loss by evaporation	Crops and forage: the humidity level will influence evaporation from canopy and soils Insects, soil bacteria, fungi, pathogens: humidity level in the microenvironment influences the survival and multiplication of some of these organisms		All stages of tree life cycle: humidity will influence the rate of evaporation from canopy, litter, and soils Pathogens and parasites: may influence survival depending on the environmental requirements of the species	Organic disease: humidity influences rate of evaporative cooling of the skin and thus the stress on the thermoregulatory system Microorganisms, parasites, and vectors: the level of humidity in the microenvironment influences the survival and multiplication of many of these pathogens
<i>Winds</i> Regional^a and seasonal changes in wind patterns (direction, force, persistence)	Surface water supply and storage: wind will affect by its effects on evaporation (moving saturated air from the water surface) Vegetation management: winds will dry soils; force of wind storms may destroy some vegetation Soils: through desertification processes (extreme drying)	Crops and forages: winds will increase evaporation of soil moisture and evaporation from canopy; wind storms may physically damage crops Soils: wind may cause soil erosion Insects, diseases, weeds: winds may spread these pests or dry out their habitat	Production and species composition of plankton (prey of fish) and survival of juvenile fish: affected by speed and direction of persistent and transient wind-driven surface currents and coastal upwelling. Plankton, juvenile fish, and the feeding abilities of adult fish and their competitors and predators are affected by wind-induced turbulence	All phases of the life cycles of trees may be affected by winds: effects on evaporation both from soils and from canopy; affects intensity and extent of wildfires; physical destruction by high winds.	Organic diseases/thermoregulation, physiology/biochemistry: winds add to the chill factor in cold weather; increase evaporation from the skin in both cold and warm weather thus influencing thermoregulation Airborne, disease-causing organisms, parasite vectors, pollens and fungi: can be disseminated or desiccated and inactivated by winds Air pollutants can be dispersed and diluted by winds. Conversely, lack of wind (stagnant air) may allow local accumulations of pollutants

Table 8.2 (continued)

Data Needed	Water Resources	Agriculture	Fisheries	Forests	Human Health
<i>Storminess</i> Changes in regional^a and seasonal occurrence and intensity of storms (combinations of wind and precipitation)	Water supply and storage: direction of movement (with respect to major streams), intensity of duration, and type of precipitation will influence amount of streamflow and storage Flooding—same as above River sedimentation: erosion and sedimentation are highest for flood-producing events	Crops and forages: decreases in intense storms may benefit, increases may be detrimental Agricultural animals (in open land)—same as above	Much of the effect of turbulence on fish and plankton may arise from intensity and location of short-term storm “events”	All stages of tree development: intense wind and ice storms may cause death (especially to largest and shallow-rooted trees) or damage (which may leave trees susceptible to disease)	Organic diseases/thermoregulation: storminess in cold weather may add to temperature stress and thus stress the thermoregulatory system
<i>Weather Types</i> (Fronts, changes in atmospheric pressure) Regional^a and seasonal changes in occurrence and type					Organic diseases: prefrontal weather types may decrease mortality from heart disease; postfrontal weather types increase disease Respiratory disease: clusters of asthma attacks appear to follow passage of cold fronts

(continued)

Table 8.2 (continued)

Data Needed	Water Resources	Agriculture	Fisheries	Forests	Human Health
<i>Changes in the Variability of Climate</i> Year to year, season to season, month to month	Changes in seasonal and annual variability of runoff influence reliability, resilience, and vulnerability of storage systems	Crop planting, sprouting and growth are dependent on warmth and precipitation at certain times. Changes in variability of temperature or precipitation may change the timing of crop planting and the production from plants Crops are damaged by spring and fall frosts and by heat waves. Decreased variability should result in fewer such extreme events, increased variability might result in more	Fish life cycles are synchronized with mean environmental conditions (i.e., temperature, turbulence, currents, plankton abundance) to optimize survival of larvae and juveniles during a critical spring and summer period. This synchronization is genetic and has limited plasticity. Variability in timing of seasonal trends can disrupt synchronization and cause reproductive failures. Weather extremes such as storms or "El Niños" also are detrimental to reproductive survival	Forests are adversely affected by storms, early and late frosts, flooding and heat waves. Should variability of climate decrease and result in fewer of these extreme events, forests should benefit. Conversely increases in variability could be detrimental	Extremes in weather (heat waves, hard freezes, snow, cold winds) are detrimental to persons in poor health, particularly those with cardiovascular or respiratory diseases. Decreases in variability of weather would probably be beneficial to these people Changes in variability could lead to changes in prevalence of some disease-causing organisms, depending on their microenvironmental requirements. For example, mosquitoes need aquatic breeding sites. In dry seasons these sites may be scarce. If precipitation is less variable (spread more evenly over the year) breeding sites may be more available throughout the year leading to an increase in numbers of mosquitoes. Increased variability might have the opposite effect
<i>Rate of Change of Climate</i>	Water storage planning: long lead times are required in planning and constructing storage systems Detection of runoff changes: rate of climate change will determine when detection of change in runoff (as opposed to natural variability in runoff) will occur. Society cannot respond to changes until they are detected	Genetic development of new crop and animal strains (for grain crops about 10 years are needed; for forage crops about 20 years are needed; cross-breeding of range animals may take some years) Planning and executing changes in irrigation and tillage practices Predicting possible rate of migration of pests	Fish stocks must remain free of exploitation a minimum of 5 years to recover from fishery collapses under even optimal environmental conditions if they recover at all. Collapses of overfished stocks can occur in one season because of severe climatic perturbators such as "El Niño." Few species can be artificially restocked	Planning reforestation (trees take 20–100 years to mature) Predicting possible rate of migration of pests	Planning changes in human shelter (ventilating, air-conditioning, heating) may possibly take 5–10 years Predicting rate at which pathogens and parasites may migrate and planning appropriate public health protective measures may possibly take 5 years

Table 8.2 (continued)

Data Needed	Water Resources	Agriculture	Fisheries	Forests	Human Health
<i>Vegetation Response to Increased Atmospheric CO₂</i> Differential species response by region^a to fertilization and evapotranspiration enhancement	Surface water supply: through effects on evapotranspiration Groundwater mining: through effects of changes in evapotranspiration of vegetation canopy on recharge and capture Water losses from storage systems: through effects on evapotranspiration by phreatophytes (plants which obtain water directly from water table) and aquatic weeds Vegetation management: vegetation response may alter the abundance and species mix of vegetation and water-use efficiency Drought: changes in vegetative canopy and transpiration may modify the effects of drought Flooding: regional changes in vegetative canopy may change interception, infiltration, and runoff and thus modify the intensity of flooding	Crops and forages: Species response may enhance production of some crops and change the geographically favorable areas for crop production Insects and diseases: vegetation response may change the susceptibility of plants to damage by those pests Agricultural animals: changes in forage may influence nutrition	Increases in CO₂ in ocean waters may increase photosynthesis and thus enhance planktonic food supplies for fishes	All stages of trees: vegetation response information needed on all stages to assess whether such things as growth, vigor, drought tolerance, and competitive advantage will be influenced	Nutrition: effects will be through effects on agriculture and fisheries

(continued)

Table 8.2 (continued)

Data Needed	Water Resources	Agriculture	Fisheries	Forests	Human Health
<i>Interactions of Climate and Vegetation Response</i> Regional and differential species changes	River sedimentation: through changes in the structure of the vegetation canopy, which affect soil erodability and overland flow of runoff Vegetation canopy changes in drainage basins	Crops and forage: changes in geographic distribution, production	Phytoplankton: effects of possible CO ₂ enrichment on sensitivity (of production and species composition) to temperature, turbulence, and currents	Forests: changes in species, abundance, geographic distribution through vegetation response	Nutrition: dependent on changes in agriculture and fisheries
<i>Rate of Increase and Eventual Level of CO₂ in the Atmosphere</i>	Through vegetation response	Through vegetation response	Fishery species, prey, predators, competitors: dissolved CO ₂ effects on changes in pH and changes in chemical species (especially trace metals and organic carbon species)	Through vegetation response	Biochemistry and physiology: effects of increased concentration in inspired air

^aRegional denotes somewhat different dimensions for each of the fields studied. Within the discipline there may also be differences. (e.g., range size of one species may differ greatly from that of another). Briefly the ranges to be considered for the different fields are as follows:

Water Resources: small drainage basins may cover only 10–20 km², the large river basins can cover thousands of square kilometers.

Agriculture: Specialty crops such as vegetables and fruits (grown in areas where soil, climate and topology are ideal) may be grown in very small areas possibly 20–100 km². Conversely, for grain crops (e.g., wheat and corn) the region may cover several thousands of square kilometers.

Forests: Many stands of forests species may cover only 50 or 60 km², others have much larger ranges.

Human Health: Studies of rates of illness and mortality may be done in cities, counties, states, or countries. However, within the larger areas there may be geographical differences that influence climate. Thus, with human health studies regions may range from 10 km² up to thousands of square kilometers.

Table 8.3
Research Needs Within Topics Studied

Fields	Research Needs
Water Resources	Knowledge of regional effects of climate change on temperature-sensitive demands for water Parameterize, explicitly, important climate and CO₂-sensitive vegetation characteristics in watershed models Develop specific methods for linking erosion from land surfaces to transport in channels and identify climate parameters relevant to erosion, transport, and sediment deposition Develop explicit linkages between climate and recharge in regional aquifer system models Integrate land and atmospheric processes; related to the hydrologic cycle, into general circulation models Evaluate methods for developing an integrated capability to estimate the indirect effects of CO₂ buildup on water resource availability and use in sensitive regions Assess the technological potential for mitigating the effects of potential water supply problems that may arise from the indirect effects of CO₂ buildup
Agriculture	Develop econometric models that evaluate the impacts of climate change on national farm production, farm policy, and foreign marketing Conduct field studies of water utilization and the economic return from irrigation Simulation studies on the need for irrigation, using climatic scenarios Test the effectiveness of existing models relating the effects of climate change to the physiology of crops Design new simulation models that account for both changes in CO₂ levels (vegetation response) and climate change Conduct field and growth chamber experiments to further estimate the required rate processes used in crop simulation models Determine the climate tolerances of specific pests Simulate the development of pests under new climate scenarios Investigate the migration potential for pests Improve pest control methods Develop simulation research for assessing the impacts of migrating cropping systems Develop soil water models for investigating the feasibility of the movement of crop zones Develop crop protein models and use sensitivity studies to investigate the impact of climate change Improve genetic development methods for stress resistant cultivars, including climate stress as a selection criteria and broadening the genetic base for food crops Study soil erosion related to changing climate Develop methods for evaluating the most effective land-use criteria, given possibility of climate change

(continued)

Table 8.3 (continued)

Fields	Research Needs
Fisheries	Improved technological, logistic, and statistical methods for locating and quantifying fish populations and growth rates Supplement existing laboratory studies on food, space, temperature, and chemical conditions suitable for the survival of fishery species at early ages Supplement existing research on mathematical models to parameterize physiological and ecological relationships and spatial and temporal variability of fisheries Supplement hydrographic data collection on the abiotic environment (winds, currents, turbulence, temperature, salinity, and pH) Conduct laboratory studies on CO₂-induced changes in water chemistry and the resultant effects on all levels of fisheries Study the effects of changes in temperature, currents, ice cover, and turbulence on the life cycles of fishery species, including food chains Study the interactive effects of changes in water chemistry, temperature, and ocean motion on the life cycle of fishery species
Forests	Gather natural history data for tree species (e.g., maximum diameter, height, age, growth rates, shade, and stress tolerance) from many global regions, in particular, tropical, subtropical, and seasonally dry regions Improve simulation models of forests response to climate change, specifically to incorporate such items as nutrient cycles, effects of chronic diseases, and atmospheric pollutants (interactions with CO₂-induced effects) Study climate influence on abundance and geographic distribution of forest pathogens and insects
Human Health	Define the extent of influence of the action and interaction of meteorological variables on the onset and progress of organic diseases and mortality from these diseases (heart, cerebrovascular, respiratory) Compare the rates of occurrence of various diseases in different climates (e.g., tropical and subtropical) with appropriate statistical methodology for determining the variance due to climate and for determining such factors as age, socioeconomic status, and cultural practices Reasons for seasonal variability in some biochemical and physiological parameters Exact relationships of meteorological variables to the abundance and distribution of some pathogens, parasites, vectors of pathogens and parasites, fungi, and pollen Interrelationships of the onset and progression of some diseases to nutrient status

Table 8.4
Some Potential Adaptation and Acclimation Measures or Processes

Fields	Measures or Processes
Water Resources	Water conservation measures, for example, enclosed water transport systems, covered reservoirs, recycling of industrial water, and residential conservation (low-flow shower heads, water-conserving toilets) Increased water storage facilities Transporting or diverting water to water-deficient areas Vegetation management in water sheds
Agriculture	Increased application of, and new innovations in, water conservation techniques for irrigation Soil moisture conservation, for example, contour planting, fallowing, wind breaks, and alternating short and tall crops for shade Genetic development of new crops, forages, and agricultural animals better adapted to changing climate Increased use of, or development of, new soil conservation techniques Migration of crops to areas where changed climate is suited to crop needs
Fisheries	Possible migration of fishery species to areas with higher survivability National and international management to limit catches and prevent fishery collapses from environmental stress Expansion of aquaculture
Forests	Migration to climatically suitable areas (because natural migration is very slow, new areas will probably need to be seeded or planted) Increased forest management, for example, irrigation at critical stages of growth and reseedling and replanting suitable areas Genetic development of trees better adapted to a new climate
Human Health	Physiological acclimation Increased attention to meteorological factors in planning and building homes and workplaces Changes in types of clothing worn Increased public health vigilance to eliminate pathogens and parasites and to prevent migration of pathogens and parasites into areas that become climatically suitable for their propagation Development of new techniques for eliminating or minimizing diseases

Note: This is not an exhaustive list, nor have these possible measures been evaluated by this study for scientific, technological, or economic feasibility.



GLOSSARY

AAAS	American Association for the Advancement of Science
ARMA	Autoregressive moving average
AR[0]	Autoregressive model of the zeroth order
ASCE	American Society of Civil Engineers
CAM	Crassulacean acid metabolism
CAST	Council for Agricultural Science and Technology
CBO	Congressional Budget Office
COE	United States Army, Corps of Engineers
DOE	United States Department of Energy
FAO	United Nations Food and Agriculture Organization
FOX	Fisheries Oceanography Experiment
GAO	United States Congress, General Accounting Office
GCM	General circulation models
GDD	Growing degree days
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
Gt C	Gigatons of carbon
HVAC	Heating, ventilating, and cooling
ICD	International Classification of Diseases
IOS	Institute of Ocean Sciences
IPHC	International Pacific Halibut Commission
IPM	Integrated pest management
IRIS	International Recruitment Investigations in the Subarctic
NCAR	National Center for Atmospheric Research
NFPA	National Forest Products Association
NIOSH	National Institute of Occupational Safety and Health
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWAFRC	Northwest and Alaska Fishery Center, NMFS, NOAA
OCSEAP	Outer Continental Shelf Environmental Assessment Program
OSU	Oregon State University
OTA	United States Congress, Office of Technology Assessment
PACLIM	Pacific-American Climate Variability Research
PBS	Pacific Biological Station
PMEL	Pacific Marine Environmental Laboratory
PROBES	Processes and Resources of the Eastern Bering Sea
SRP	Salt River Project
SUPER	Subarctic Pacific Ecosystem Research
TDS	Total dissolved solids

UA
UBC
UNEP
UNWC
USDA
USGS
UW
WCRP
WHO
WMO
WRC

University of Alaska
University of British Columbia
United Nations Environment Programme
United Nations Water Conference
United States Department of Agriculture
United States Geological Survey
University of Washington
World Climate Research Program
World Health Organization
World Meteorological Organization
United States Water Resources Council

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