THE GREENHOUSE EFFECT: RECENT RESEARCH AND SOME IMPLICATIONS FOR WATER RESOURCE MANAGEMENT

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Applications Information Center
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PREFACE

This paper is one of a series on research in progress in the field of human adjustments to natural hazards. The series is intended to aid the rapid distribution of research findings and information. It was started in 1968 by Gilbert White, Robert Kates, and Ian Burton with National Science Foundation funds but is now self-supporting. The papers are produced by:

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SUMMARY

This paper describes some of the issues associated with potential anthropogenic global warming (the "greenhouse effect"), especially those of interest to water resource planners and managers. We describe the basis for growing concern that the global climate will warm at a rate unprecedented in human history over the next several decades, giving particular attention to uncertainties in predictions of climate change, and to methods for creating climate scenarios useful in studying impact and assessing response options.

We then review the literature regarding the impacts of climate change on water resources, finding indications in existing research that even small climate changes could lead to serious problems in water supply, flood control, and other resource planning areas. Water resources are immediately sensitive to climate change and potentially adversely affected by change in any direction: there could be more floods or more droughts in a "greenhouse world." Less evidence is available concerning potential climate impacts on elements such as water quality, user demand, and other environmental systems dependent on water such as fisheries and wildlife.

We conclude that the increasingly credible predictions of global warming and growing public concern now focused on the issue means, simply, that water resource managers must now seriously consider the potential for future climate change. However, the evidence does not currently recommend drastic changes in the planning and operating of water systems; it is not

yet time to begin designing systems differently. But, in connection with growing public concern, managers need to monitor closely developments in climate change research, assess how sensitive their systems are to climate fluctuations, and start to canvass feasible responses to rapid climate change.

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WHAT GROWING CONCERN OVER THE GREENHOUSE EFFECT MEANS TO NATURAL RESOURCE MANAGERS

The drought and heat wave which affected much of the United States during the summer of 1988 may well be remembered as the event which firmly imbedded the threat of global warming into the public and policy-maker consciousness. Both Time and Newsweek featured cover stories on global warming and ozone depletion, and congressional hearings, international conferences, and even discussions of a global treaty on climate protection, have placed the issue near the top of the political agenda.

The events of 1988 accelerated a growing concern fueled by increasingly credible predictions that anthropogenic climate changes are likely to emerge from natural climatic variability, or "noise", in the next decade or so. Global average temperatures $3^{\circ}C$ to $5^{\circ}C$ warmer than present are expected to result from the doubling of greenhouse gas concentrations sometime near the middle of the next century (see, for example, World Meteorological Organization, 1985; Schneider, 1989). Some analysts feel that greenhouse climate change is currently underway, or is imminent (Hansen, et al., 1988; Hansen and Lebedeff, 1988), and scientists point out that the warmest years since instrumental records began in the late 1800s have occurred in the 1980s.

Calls for Action

Impact projections indicate that even climate changes less than those expected to accompany a doubling of atmospheric carbon dioxide (CO_2) (along with increases in other greenhouse gases) can disrupt natural resource systems. This has led to calls for concrete policy actions even before current uncertainties are much reduced.

Although government response thus far has been only to urge and support further study, several credible social institutions have recommended more overt action. A March 1988 letter from 42 United States senators to President Reagan noted that "greenhouse gases will lead to substantial changes in the climate of our planet with potentially catastrophic environmental and socio-economic consequences." The senators called for

> the establishment of a high level working group to study potential responses to climate change, including greenhouse gas emissions reduction and adaptation [and] negotiation of a greenhouse gas convention.

The United Nations Environmental Programme (UNEP), which orchestrated the international protocol on ozone protection in 1987, urged the

> establishment of an intergovernmental coordinating body on climate change . . . 1995 is UNEP's target date for "agreement on appropriate and timely measures" to deal with climate change. With the ozone layer accord as a precedent, there is a reasonable expectation for successful international action. (United Nations Environment Programme, 1988, p. 1)

The declaration of the World Conference of the Changing Atmosphere held during June 1988, in Toronto, Canada, calls for "an international framework convention . . . as well as national legislation to provide for protection of the global atmosphere," with the goal of reducing CO_2 emissions by approximately 20% of 1988 levels by the year 2005, and an ultimate reduction of 50% some time during the next century (World Meteorological Organization, 1989).

These calls for policy response have focused mostly on the need to reduce anthropogenic greenhouse gas emissions in order to limit, or at least delay, global warming. Less attention has been given to the question of whether systems for managing climate-sensitive resources such as water and forests can adapt to changes anticipated over the next few decades. Better understanding of adaptive potential is important because some climate change is likely in the near future even if greenhouse gas releases are reduced immediately (Jones et al., 1988). Due to past releases of greenhouse gases and to the thermal inertia of the atmosphere-ocean system, we are already "committed" to some degree of global warming.

A Resource Planning Conundrum

The greenhouse effect thus presents environmental managers with a unique planning conundrum. On one hand, global warming may have drastic and irreversible effects on resource systems being designed and implemented today, and anticipatory, rather than reactive, adjustments may be needed to ameliorate future impacts. On the other hand, predictions of global warming contain a great deal of uncertainty, and scientists continue to debate the rate, spatial distribution, and physical details of greenhouse effects, and to disagree over the strength of empirical evidence for global warming, as described later in this paper.

Nevertheless, resource planners may soon be forced by public and political pressure to take actions to mitigate future climate impacts before the uncertainty is much reduced. Legislation to reduce and prepare for the greenhouse effect was introduced into the U.S. Senate during the summer of 1988 (Senate Bill 2667, the National Energy Policy Act, cf. Congressional Record, July 28, 1988), and credible social institutions worldwide are calling for preparatory action to prevent and/or adjust to global warming (United Nations Environment Programme, 1988). The U.S. Environmental Protection Agency's reports to Congress on climate change effects (Smith and Tirpak, in press) and the potential for limiting global warming (Lashof and Tirpak, in press), will surely stimulate additional policy concerns.

In this policy environment, then, resource managers need to be aware of the greenhouse issue and of the research which is driving public concern. This paper is meant to inform water resource managers about some of the research on, and implications of, the greenhouse effect. It first describes recent studies pointing to global warming and identifies some of the strengths, weaknesses, and points of controversy in those results. It then describes how scenarios of future climate are created for use in impact studies. Next, specific impact assessments focused on water resources are reviewed. Finally, a brief annotated bibliography is provided to give the water resource planner a further base in the relevant literature.

RECENT RESEARCH ON THE GREENHOUSE EFFECT

The theory of the greenhouse effect is one of the least controversial in atmospheric science. Radiatively affective greenhouse gases like carbon dioxide (CO_2) and methane (CH_4) are relatively transparent to incoming (short-wave) solar radiation and relatively opaque to outgoing (long-wave) terrestrial radiation. As they accumulate in the atmosphere due to release by human activities such as the consumption of fossil fuels, production of food (e.g., rice cultivation releases methane), and destruction of forests, these gases tend to push the earth's radiation budget toward the net positive, thus inducing climate warming. The main controversy surrounding the greenhouse effect is the rate and distribution of warming (and other climate changes) which will be associated with increased production of greenhouse gases (Schneider, 1989). Unfortunately for water resource managers, greenhouse climate predictions regarding precipitation are even less certain than those concerning expected temperature changes. Several additional uncertainties regarding predictions of the greenhouse effect are described below.

There is no doubt that the chief greenhouse gas, carbon dioxide, has been increasing since the Industrial Revolution of the 19th century (Figure 1). Measurements since 1958 show about a 10% increase of atmospheric CO_2 (Figure 2), and estimates of energy use, forest destruction, and the fraction of CO_2 held in the atmosphere indicate that the pre-Industrial Revolution concentration of CO_2 will have doubled by the middle of the 21st century. Other greenhouse gases (e.g., N_2O, and chlorofluorocarbons--CFCs) will enhance the effect. In addition, CO_2-induced global warming will lead to an increase in the water vapor content of the atmosphere. Higher amounts of atmospheric water vapor will also contribute to warming, though the effect of increased cloudiness remains unclear; it could reduce or increase the warming.

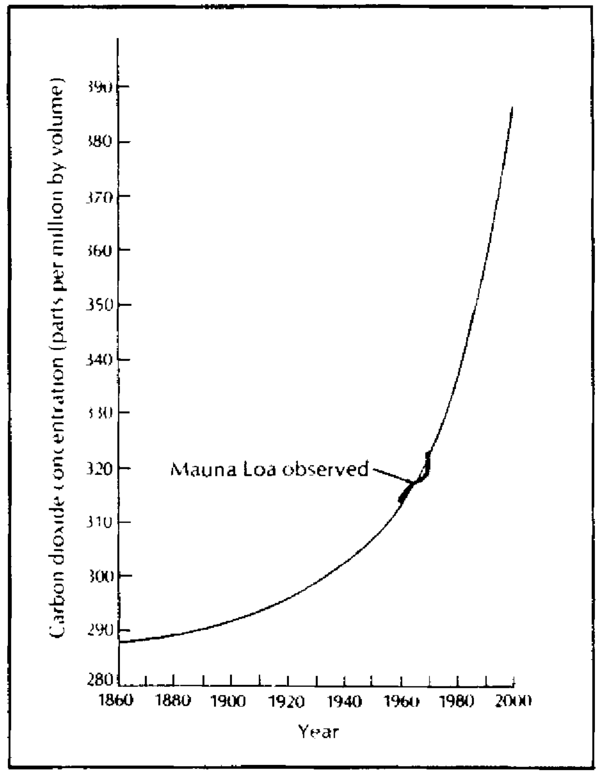

FIGURE 1

INCREASE OF CARBON DIOXIDE IN THE ATMOSPHERE SINCE 1860

Source. Anthes, 1981

As described below, climate simulations with doubled amounts of greenhouse gases indicate a climate significantly different from today's. Warming of 3°C to 5°C on average is expected, pushing the climate into a state not experienced since historical

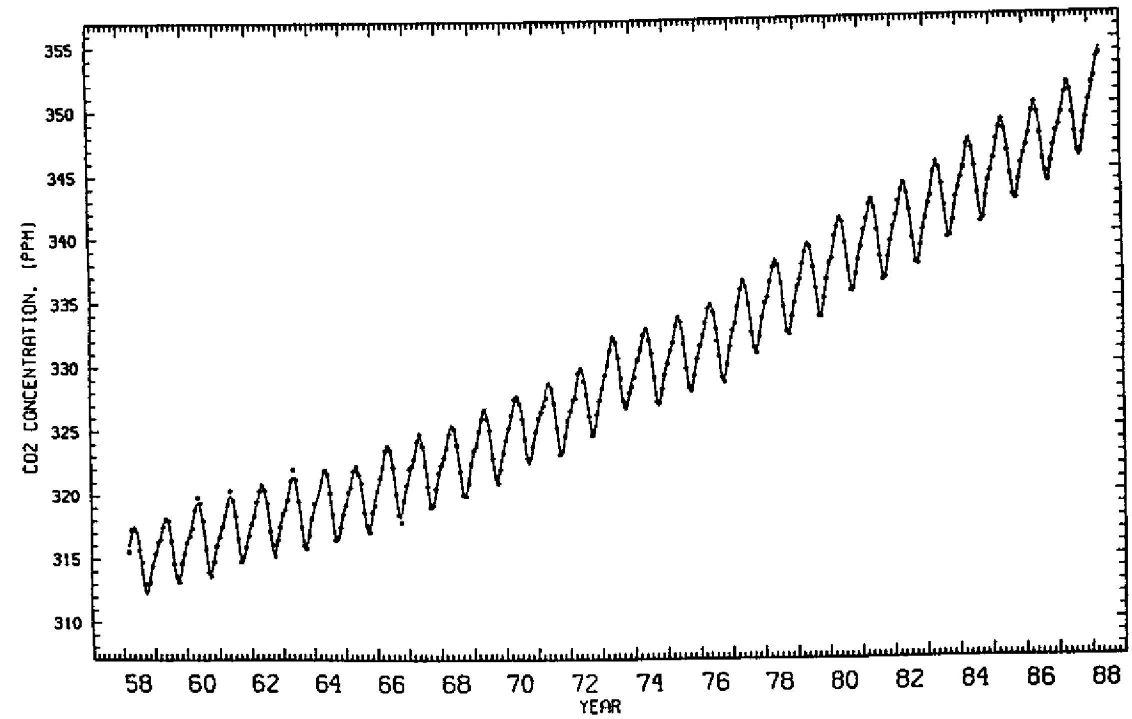

FIGURE 2

INCREASE IN ATMOSPHERIC CO_2 SINCE 1958 OBSERVED AT MAUNA LOA OBSERVATORY.
Source: Keeling et al, 1982 (updated 1988)

civilization emerged several thousand years ago. Studies of the impacts of this warming on agriculture (Parry et al., 1988), water resources (Cohen, 1986; Gleick, 1987), and forests (Shugart et al., 1986), indicate dramatic, disruptive, and potentially irreversible effects. Indeed, an even smaller climate change, say a $1^{\circ}C$ warming, could significantly affect natural resource systems.

The Evidence For Global Warming: Global Mean Temperature Trends Of The Past Century

The primary measure of global climate change is the change in annual mean global surface air temperature. Although other changes in climatic patterns (precipitation patterns or changes in intensity, frequency, and/or duration of threshold events like droughts and floods) may well be of greater importance to resource managers, there is little consensus on the direction or magnitude such changes might take. Due to the widespread agreement that increasing amounts of greenhouse gases in the atmosphere will result in a global warming, global annual temperature is the most frequently cited indicator and is being carefully studied to search for the "signature" of global warming. Other changes in characteristics of the climate system may also indicate global warming (e.g., stratospheric cooling). However, the record of large-scale average surface temperature comprises the only data of sufficient quality and length to permit the determination of a well-defined level of climatic noise (Wigley et al., 1985).

The most credible, quality-controlled global temperature series has been constructed by researchers at the Climate Research Unit in Norwich, U.K. Their temperature record back to 1900 (Figure 3) shows roughly a .5°C warming, highlighted by the warm years in the 1980s. In a recent analysis of these data, Jones et al. (1988) conclude that

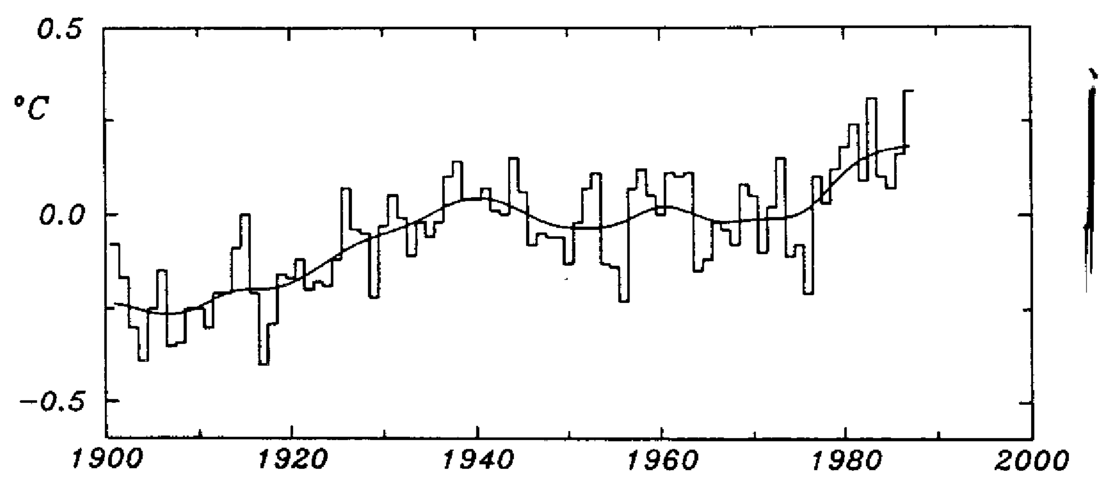

FIGURE 3

20th CENTURY GLOBAL SURFACE AIR TEMPERATURE

Source: Jones et al., 1987

> the persistent surface and tropospheric warmth of the 1980's which, together with ENSO, gave the exceptional warmth of 1987 could indicate the consequences of increased concentrations of CO_2 and other radiatively active gases in the atmosphere.

In a 1988 paper, Hansen and Lebedeff of the Goddard Institute for Space Studies (GISS) analyzed a similar, but slightly less complete (in number of stations), record of global mean temperatures over the past century. They also found a steady increase (Figure 4). The more important indication of warming is seen in the last ten years of their graph. As the authors stated,

> 1987 was approximately as warm as 1981, the warmest previous year in the record. The 1980's are the warmest decade in the history of instrumental records, with the

four warmest years on record all occurring in the 1980's. (Hansen and Lebedeff, 1988)

In addition, 1988 was as warm as 1987. The drought and exceptionally warm temperatures which plagued the U.S. during the summer of 1988 added credence and drama to Hansen's testimony to the Senate Energy Committee in June of that year in which he remarked that the greenhouse effect was "99%" likely to be associated with the recent warming trend of the instrumental record (see Schneider, 1989), and that he was confident greenhouse warming had begun.

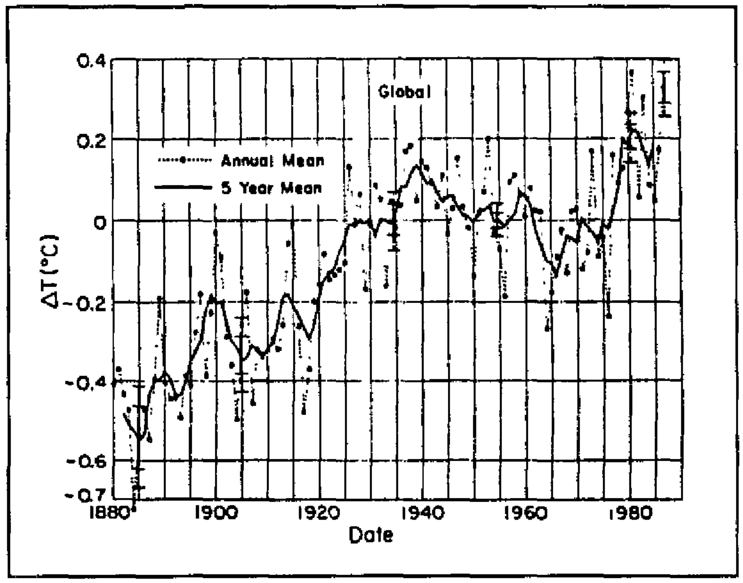

FIGURE 4

GLOBAL SURFACE AIR TEMPERATURE CHANGE

Source: Hansen and Lebedeff, 1988

In order to assess the significance of this increased global warming, Hansen and Lebedeff compared the 1987 global temperature to temperature trends of the period 1951-1980, a period used to represent "normal" climate. The standard deviation of annual average global temperature during this 30-year period was 0.13°C. The departure of the 1987 global temperature from this mean was 0.33°C, representing a warming of between two to three standard deviations (2-3σ). As the authors stated, if a warming of three standard deviations (3σ, i.e., 0.39°C) is reached, "it will represent a trend significant at the 99% confidence level" (Hansen and Lebedeff, 1988).

Determining whether this pattern derives from the greenhouse effect is replete with difficulty. There have been many sharp fluctuations of climate in earth history, and it is impossible to prove, at this time, whether the global warming trend highlighted by the 1980s warmth is a greenhouse fingerprint or merely natural climatic variability. H.H. Lamb described this problem in 1982 when he wrote, "The record of prevailing temperatures . . . shows that the range of variation is itself subject to variation" (Lamb, 1982). However, recent temperature trends represent a compelling argument for global warming, though careful climate researchers seem forced by obligatory scientific agnosticism to say that the pattern is "not inconsistent" with expectations of greenhouse warming. Still, some atmospheric scientists are fairly convinced that the recent warming trend is associated with the greenhouse effect as Hansen's remarks above demonstrate.

While the temperature record provides the empirical base for concerns over global warming, it is projections based on sophisticated computer models of the climate system that yield the greatest concern and potentially can provide critical planning information for natural resource managers.

Projecting Future Climate Changes

There are two primary methods used to project changes in climatic patterns resulting from the greenhouse effect: general circulation models (GCMs) and climatic analogs. Arbitrary increments reflecting the patterns derived from these two methods are also used in climate impact studies. GCMs have been found to be reasonably accurate on a global scale but to produce inaccuracies and uncertainties at the regional scale. They also provide information on average conditions, not discrete events like floods, though some implications for extremes have been drawn from the models, as discussed later. Climate analogs are more applicable to future climate impact assessment on a regional or local scale. Each approach is described below in more detail.

General Circulation Models

There are currently four primary institutes in the United States which conduct the type of computer modeling necessary to project global climate changes associated with the greenhouse effect: 1) Goddard Institute for Space Studies (GISS), in New York City; 2) Geophysical Fluid Dynamics Laboratory (GFDL), in Princeton, New Jersey; 3) National Center for Atmospheric Research (NCAR), in Boulder, Colorado; and 4) Oregon State University (OSU), in Corvallis, Oregon. Although differences exist in the techniques and results of these four models, none of the models appears to have a higher degree of certainty or reliability than the others. All four models predict global warming with greenhouse gas growth.

A GCM is a three-dimensional computer model consisting of a series of mathematical equations which describe the physical and dynamic processes of the global climate system. The model describes the rates of change of atmospheric variables such as temperature, air pressure, water vapor, and wind velocities (both horizontal and vertical). Equations such as the thermodynamic equation, the hydrodynamic equation, and the ideal gas law are employed to model this behavior.

Due to the limited spatial resolution of a GCM, explicit resolution of small-scale variables (e.g., individual storms) is not possible, though such elements are an important part of the climate system. The usual procedure to determine these variables (which include transfers of solar and terrestrial radiation, turbulent transfer of heat, and cloud cover) is paramaterization --that is, "to relate them either statistically or empirically to the scale of those variables which <u>are</u> resolved" (Bach, 1988, emphasis added). One of the main weaknesses of GCMs lies in these sub-grid processes that must be parameterized in some way rather than explicitly computed. Vertical transfers, or "fluxes," of heat and moisture are obviously of tremendous importance in the general circulation. Hence, the paramaterization of these smaller-scale motions affects the resolved large-scale behavior.

The GISS model was selected as an example of a GCM because it most closely meets the criteria for a reliable GCM, as proposed by Bach (1988). Such a model, he states, should

1) be based on a realistic geography and topography;
2) have a high spatial resolution;
3) have an adequate temporal resolution;

4) incorporate a coupled model of the atmosphere-ocean circulation; and

5) simulate realistically the pattern of the observed climate.

The GISS GCM divides the earth into grid boxes (Figure 5), each with the generally appropriate land cover and elevation, as illustrated in the digital maps in Figure 6. The climate-process equations are solved for each grid box, and "the transfer of

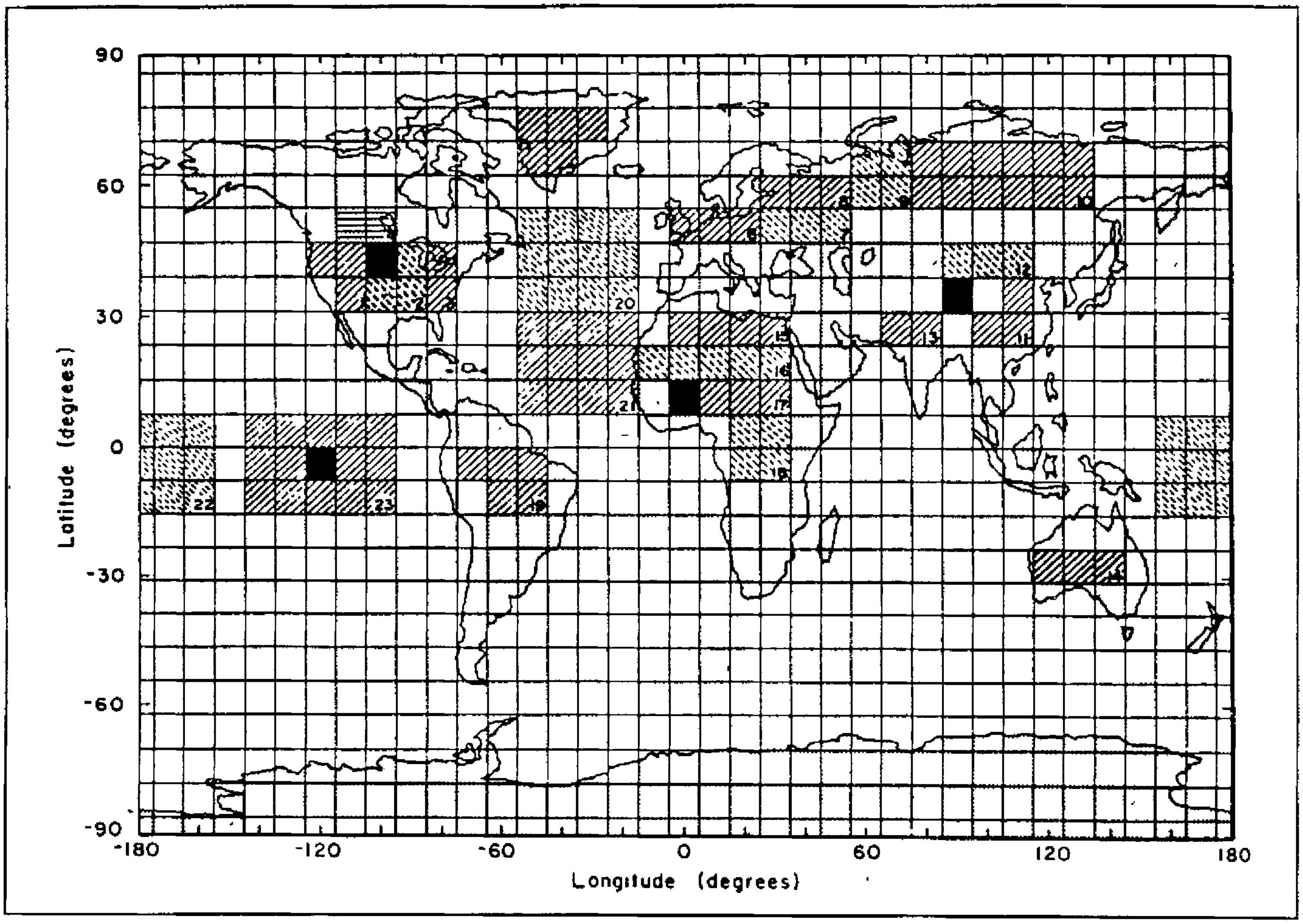

FIGURE 5

GRID SPACING FOR 8° BY 10° MODEL

(Shading indicates boxes for special study)

Source: Hansen et al., 1983

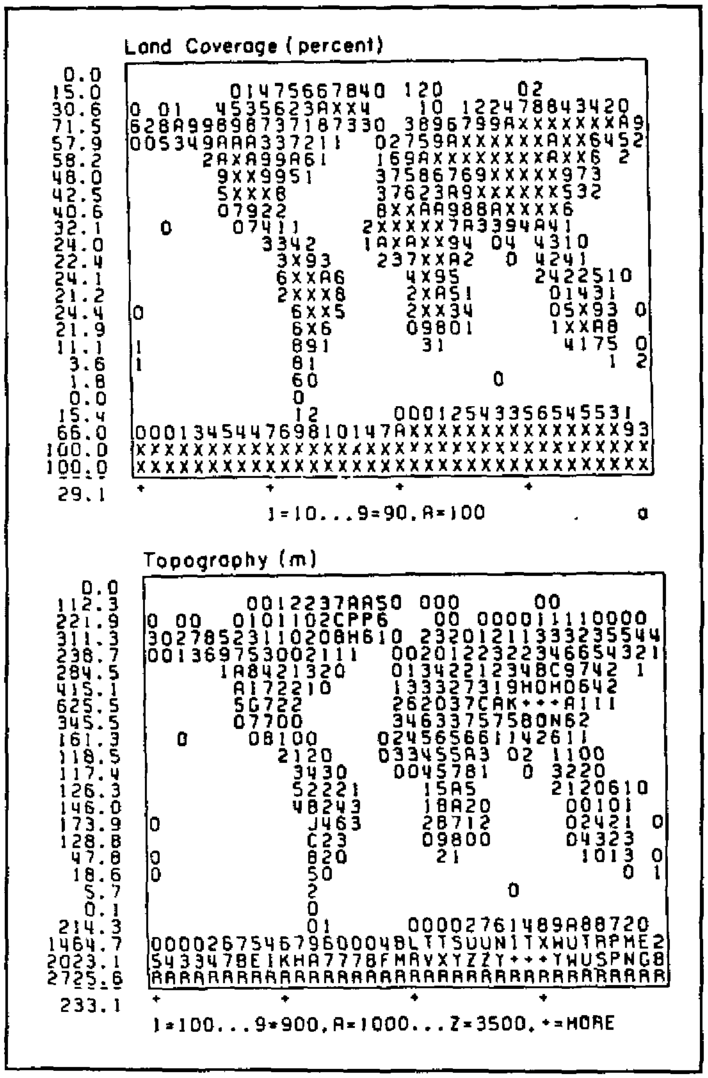

FIGURE 6

DIGITAL MAPS OF LAND COVERAGE AND TOPOGRAPHY FOR 8°x10° MODEL

A blank on either map above is identically zero. For land coverage 0 is 0-5%, 1 is 5-15%, A is 95-100%, and X is exactly 100%. For topography 0 is 0-50 m, 1 is 50-15- m and + is more than 3550 m. Longitudinal averages are on the left, above the area-weighted global average.

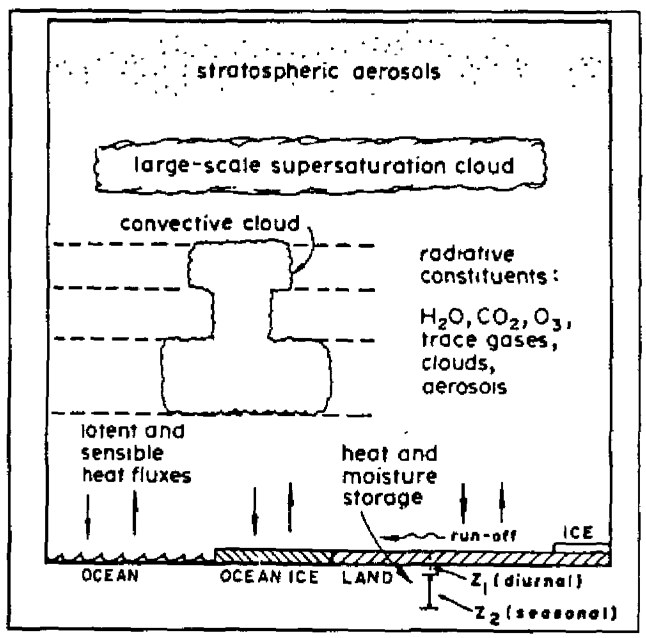

FIGURE 7

SCHEMATIC ILLUSTRATION OF MODEL STRUCTURE AT A SINGLE GRID BOX

Source (both figures) Hansen et al., 1983 mass, energy, and momentum from one box to another and also . . . physical processes within the boxes which represent sources and sinks of these substances" are calculated in iterative computer runs (Bach, 1988). The general structure of each grid box is shown in Figure 7. Each grid box is divided into nine vertical layers and covers 8° latitude by 10° longitude of the earth's surface. This is the basic information unit available to climate impact assessors.

The principle underlying the use of these grid boxes (or grid points, when the boxes are plotted as points rather than areas) is that the atmosphere may be represented by values of a number of basic variables at a finite number of locations arranged in a three-dimensional array. As mentioned, the GCM is composed of a matrix of variables--the number of vertical layers, nine in the GISS model, times the number of horizontal grid boxes or grid points, times the number of atmospheric variables defined (commonly seven). These numbers define the state of the model atmosphere at an instant in time. The task of the computer simulation is to calculate how each of the variables will change during a period of time; in other words, to predict the evolution in time of the model atmosphere from some initial state.

Due to the important role which the oceans play in the climate system, it is important that GCMs incorporate interactions between the atmosphere and the oceans. There have been a number of different ways in which GCMs have attempted to model oceanic circulation and heat transport (see Meehl, 1984). The

GISS model uses a "60-70 meter mixed layer with prescribed seasonal depth and prescribed horizontal transport" (Bach, 1988). That is, the model simulates seasonal changes in heat storage, as well as poleward heat transport. However, even more realistic simulations of ocean dynamics and ocean-atmosphere interactions must be achieved in order to improve the credibility of GCMs. The "coupling" of the oceans and atmosphere is one of the problem areas in climate modeling today (Gates, 1985).

For those interested in the impacts of increasing atmospheric levels of carbon dioxide, the attraction of a GCM is that it is capable of modeling the effects of atmospheric disturbances on the evolution of the atmosphere. Such disturbances which are external to the "climate system" (defined by Mitchell (1976) as the combination of atmosphere, oceans, land surface, ice masses, and the biosphere) are referred to as "external forcing mechanisms." In addition to anthropogenic influences, other external forcing mechanisms include changes in solar variability, volcanic eruptions, or earth orbit changes.

Although GCMs are the "state-of-the-art" method for constructing future climate scenarios, they include weaknesses that inhibit their accuracy, especially:

1) incomplete knowledge,
2) insufficient spatial resolution, and
3) time constraints.

Incomplete knowledge. The main difficulty in using GCMs as predictors is that GCMs cannot provide an exact replica of the actual climate system. This is due to science's incomplete understanding of physical processes in the atmosphere. Especially lacking is knowledge on processes such as convection, the role of vegetation and soil in the transfer of moisture and heat, and small-scale ocean mixing. Such phenomena need to be better understood before GCMs can be dramatically improved. Several credible members of the modeling community predict that many of these constraints (e.g., cloud feedback) can be significantly lessened with five to ten years of concerted research.

Spatial resolution. Spatial resolution is another problem with GCMs. Even the smallest grid size currently in use (4° latitude by 5° longitude in the Oregon State University model) is too large to permit accurate modeling of smaller scale processes, such as the formation of individual storm cells. Also, because of significant variation which may exist within a grid cell, there is debate among modelers whether data for a single grid point can be used as a valid indicator of climate at a specific location (e.g., within certain drainage basins or a specific city). Differences in topography within a grid cell may result in significant climatic differences within an individual cell.

There may also be significant differences between adjacent cells. Cohen (1986) addressed this problem by conducting a "sensitivity test" for the Great Lakes area. This test consisted of shifting cells one grid value to the east, west, and north. Values of annual average precipitation for the observed and simulated current climate were compared to assess the sensitivity of outcomes to spatial shifts. The shifting of the grid cells resulted in a range of nearly 180 mm between the lowest and highest values for annual basin precipitation--roughly 20% of mean annual precipitation. This indicates the great uncertainty in determining the location of simulated future anomalies, as well as the sensitivity of results to the choice of grid value for analysis. It also highlights the great deal of work that still needs to be done on evaluating regional impacts resulting from global climate change--a difficulty often referred to by impacts researchers as the "climate inversion problem" (i.e., interpolating climate changes on small scales from large-scale statistics generated by GCMs. The term "climate inversion" is used because it is the reverse or inversion of the process of GCM building (Kim et al., 1984), in which the model builder aggregates meteorological processes to the model scale).

Time constraints. A third problem with GCMs is the excessive computing time they require. Since greenhouse gas concentrations are increasing over time, the most appropriate application of a GCM would be to conduct a "transient response" study in which the greenhouse effect in the model is incrementally increased rather than simply doubled or quadrupled. However, few transient response GCM simulations have been conducted to date because they must be carried out over extended periods of time (Meehl, 1984). Therefore, the method currently used is a "step increment run" (also referred to as an "equilibrium response" study) to determine climate perturbations for a prescribed future increment increase of greenhouse gases (usually doubling). The model is then run long enough under the new conditions for the various atmospheric variables to "stabilize"; average statistics are then derived. There is some debate over the reliability of this method (Thompson and Schneider, 1982).

Alternative methods of climate scenario construction also provide valid approaches to climate impact assessment; however, because the accuracy and efficacy of GCMs will continue to improve in the future, climate impact modeling utilizing their output will probably continue to be the most common type of impact projection.

Given the current weaknesses of GCMs, however, it is only prudent that climate impact assessors also employ other approaches to the generation of future climate scenarios. Two are most useful: climatic analogs and arbitrary increments.

Climatic Analogs

Analogs, based on the premise that the past is the key to the future, usually take one of two forms: 1) paleoclimatic reconstruction of broad patterns of warm periods, based on various indicators of past climate (e.g., tree rings, pollen cores, etc; such indicators are collectively known as "proxy data"); and 2) use of the modern instrumental record to create warm period analogs. Such scenarios usually use a composite of warm years, not necessarily consecutive, from the period of good instrumental observations--ie., the last 80 years.

Flohn (1977) has identified four possible candidates for paleoclimatic analogs to future global warming: 1) the medieval period of roughly 800-1200 A.D.; 2) the Holocene warm period known as the Hypsithermal, Altithermal, or postglacial warm period, roughly 4000 to 8000 years before present (ybp); 3) the last interglacial period, about 120,000 ybp; and 4) the last period of an ice-free Arctic Ocean, before 2.5 million years ago.

These periods, all representing relatively warm epochs in earth history, are possible analogs for progressively warmer future climates. As Flohn points out, however, the extent to which these periods are good analogs depends on how closely past conditions at the earth's surface (e.g., the extent of polar ice fields, sea surface temperatures, etc.--collectively known as "boundary conditions") compare to possible future conditions. In all four of these periods, boundary conditions were quite different than they are today, and may be in the future. In addition, the data used to create these paleoclimatic scenarios are usually quite sparse and generally of an indirect and qualitative nature (e.g., pollen analysis).

An underlying assumption in using such past warm periods as future analogs is that whatever the cause of the warming, there will be broad similarities in the patterns of climatic change. Indeed, numerical model results indicate that there are broad similarities in the patterns of climatic change (Manabe and Wetherald, 1980). There is additional model and observational evidence both supporting and contradicting this assumption (Wigley and Webb, 1985).

In summary, paleoclimatic reconstruction can provide a general picture of possible future warmer climates; however, a researcher must be aware of the limitations and uncertainties implicit in such scenarios and refrain from placing too much faith in them. Such scenarios are not predictions; they act merely as guides to the types of climatic conditions that are possible in a high-CO_2 world.

In addition to using proxy climatic data from the distant past, scenarios can be based on instrumental measurements made during the 20th century. These instrumental analogs were constructed by selecting a set of warm and cold years (not necessarily consecutive) from the 20th century climatic record. Spatially and temporally detailed composites of the differences in temperature, surface pressure, and precipitation between the two sets are then compiled. Alternatively, groups of recent warm years can be compared with the long-term mean to derive warm-world scenarios (Wigley, et al., 1980).

Advantages of this approach to climatic scenario construction are its greater degree of spatial detail (versus GCMs) and, since this method is based on recent records of climatic fluctuations, a high degree of realism. However, climate warming associated with future increases in atmospheric carbon dioxide will likely exceed the range of temperature fluctuations witnessed in the 20th century, creating what climatologists refer to as a "no analog" situation. Also, the instrumental-scenario approach tells us nothing about possible "transient responses" of the atmosphere to steadily increasing levels of greenhouse gases; this approach suggests a possible future planetary climatic condition, but does not portray constantly changing atmospheric conditions between the present and the future atmospheric state.

Arbitrary Increments

Studying the effects of simple, convenient increments (e.g., a 10% change in precipitation and a 2°C change in temperature) is another approach to developing plausible climate scenarios and testing the sensitivity of natural resource systems to climate change. Increments of change in temperature and/or precipitation values are chosen by the impact assessor to simulate future climatic states generally consistent with GCM-predicted changes or past climatic fluctuations. Arbitrary increments are valuable because the selection process conveys its own caveat: they are rough estimates, whereas the greater detail of analog or GCM scenarios may suggest more reliability than is warranted. Typical values used in this process are ± 20% precipitation and ±1°C or 2°C temperature changes--similar to changes that the GCMs indicate may occur over the next few decades.

Uncertainties in Predictions of Future Climate Change

Predictions of future climate change are shrouded in uncertainty. Indeed, due to the complex nature of the atmosphere and its general circulation, finely tuned predictions of atmospheric responses to external forcing mechanisms, such as increasing levels of carbon dioxide, will probably not be available in the next few decades. Moreover, simulations of future greenhouse forcing are based on estimates of future gas emissions, thus requiring projections of uncertain social development as well as atmospheric evolution.

Improved GCMs probably represent the best hope for long-range modeling of atmospheric evolution. To provide a better sense of the nature of GCM predictions, the following section discusses the results of a recent major effort to model atmospheric response. It involved three different scenarios of atmospheric composition, based on assumptions of global gas emissions. This study by James Hansen and his colleagues at the Goddard Institute for Space Studies (GISS), Columbia University, has attracted considerable attention among policy makers and the general public.

General Trends and Mean Conditions

Hansen et al. (1988) used the GISS GCM to examine the transient response of the atmosphere in three different scenarios of trace gas (CO_2, water vapor, and other gases present in trace amounts) growth. The scenarios were designed to yield a broad range of atmospheric responses to future levels of greenhouse gases. Scenario A represented exponentially increasing future emissions of greenhouse gases. Due to economic and environmental limits on development, this scenario is probably on the "high side" of reality. Scenario B, the most plausible future scenario, involved decreasing trace gas growth rates, and thus the annual increases in "greenhouse forcing" remained roughly at the current level. Scenario C involved drastically reduced future growth of these gases.

Computed surface air temperatures for these three scenarios are shown in Figure 8. All three scenarios indicate that global warming to the temperature levels attained at the peak of the current interglacial period, as well as the previous interglacial, will be reached--even for the most conservative greenhouse gas scenario.

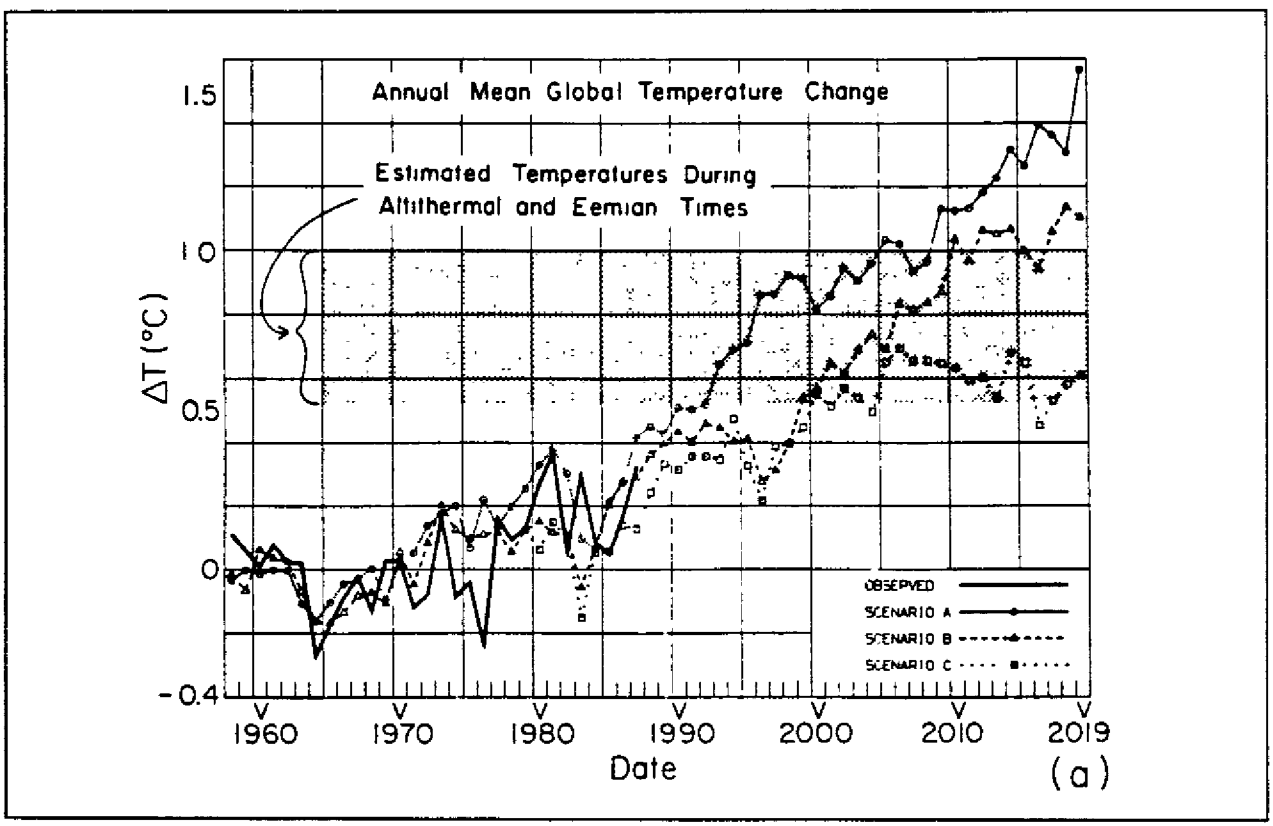

FIGURE 8

SURFACE AIR TEMPERATURES UNDER THREE SCENARIOS

Source: Hansen et al., 1988

Another important model result is the prediction of global warming to a level at least three standard deviations (σ) above the average global temperature of 1951-1980, a period commonly used as a reference to define "normal" climate. The standard deviation about this 30-year mean is 0.13°C; hence, a warming of only about 0.4°C is significant at the 3σ level (99% confidence level). Such an increase, according to the authors, "should be clearly identifiable in the 1990's" (Hansen et al., 1988).

An estimation of the impacts of greenhouse warming on the frequency of extreme temperatures was also conducted. It is important to note that these estimates assumed that the distribution of temperatures about the mean would not markedly shift as the mean increased in response to greenhouse warming (an assumption that the authors felt safe making; changes in climatic variability and extremes will be further discussed in the next section). This was done by comparing model-predicted warming for a given decade against local daily temperatures for the period 1950-1979. The ten hottest summers (June-July-August) of the 1950-1979 period were arbitrarily defined as "hot", the ten coolest as "cold", and the remaining ten as "normal". The researchers used the analogy of a rolling six-faced die to represent the probability of a summer coming up as "hot."

> With hot, normal, and cold summers defined by 1950-1979 observations described earlier, the climatological probability of a hot summer could be represented by two faces (say painted red) of a six-faced die. Judging from our model, by the 1990's three or four of the six faces will be red. (Hansen et al., 1988)

Although long-term, average global atmospheric warming is certainly of importance, the possibility of changes in the frequency and/or magnitude of extreme events is probably of greater concern to the water resource manager, as discussed next.

Climatic Variability and Extreme Events

Nearly all contemporary studies of the physical characteristics of climatic change, as well as studies of the attendant societal implications, operate on the premise that there will be no major changes in climatic variability accompanying global warming. Yet, changes in the magnitude and frequency of extreme events are potentially more threatening to water resource management than are shifts in mean values. For instance, most of the structures designed for flood control and water supply in this country have been designed under the assumption that past climatic extremes (e.g., floods and drought) will continue to occur with similar frequency and magnitude in the future. Changes in the variability of climate would magnify the impact of climate change on society (Mearns et al., in preparation).

Studies of changes in long-term, globally averaged temperatures in association with increasing atmospheric levels of radiatively active gases have been conducted for roughly 20 years (e.g., Manabe and Bryan, 1969). However, analyses of changes in climatic variability and extreme events which may attend relatively slow shifts in climatic means are just getting underway. A 1988 investigation by Rind and his colleagues used the GISS GCM to examine possible changes in variability of temperature and precipitation due to climate change. Both a doubled CO_2 run, as well as a transient climate change experiment (Hansen et al., 1988), were used. Before trying to predict future changes in variability, however, the results of the control run, which used estimated 1958 values of atmospheric composition, were examined to see how well they recreated observed monthly means for four different months. The results of the control run were compared to observed temperature and precipitation values in four regions of the U.S.: the Great Plains, the Southeast, the Great Lakes region, and the West Coast (Figure 9).

The model produced significantly different temperature and precipitation values for roughly half the cases. This inability to recreate present mean conditions raises doubts about its ability to project future changes in variability. It also illustrates the complexity and uncertainties in understanding the climate system.

The modeled interannual variability of temperature and precipitation was tested by examining modeled standard deviations (both in the control run as well as the doubled CO_2 run) against observed interannual standard deviations for each month in all four regions. For temperatures, there was good agreement between the observed and modeled variability, although the model tended to overestimate summer temperature variability. There was less agreement between modeled and observed precipitation variability,

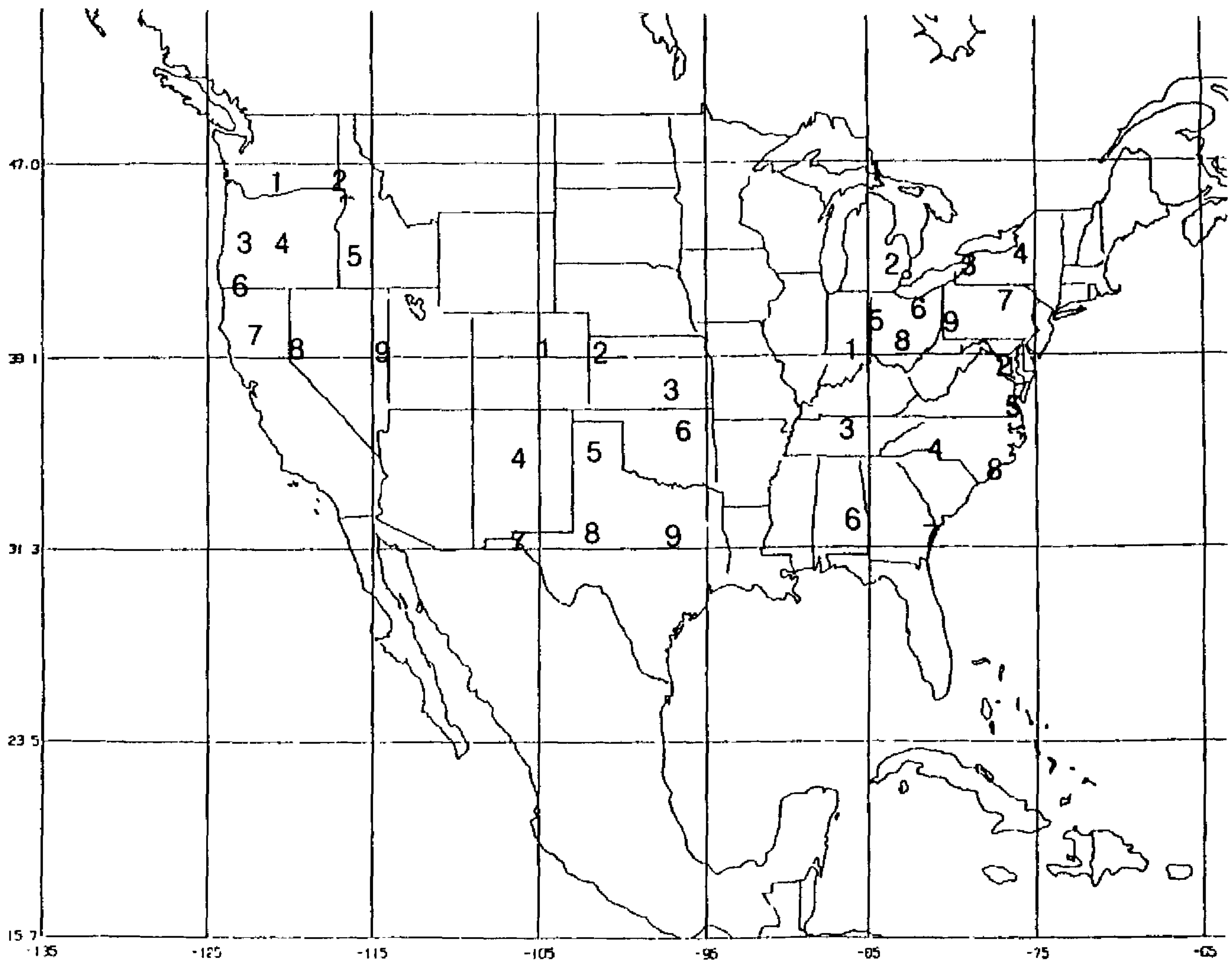

FIGURE 9

GRID BOXES AND CITIES USED IN THE RIND et al. STUDY
(Cities indicated by numbers)

Source: Rind, 1988

with model variability generally larger than observed. At least part of this difficulty can be attributed to the manner in which precipitation values are averaged for the grid box of interest. As the researchers state, "When we reduced the number of stations used for assessing the observed variability from nine to five, precipitation variability increased by some 33%, while temperature variability was relatively unchanged" (Rind et al. 1989). That is, even "observed" precipitation variability for a grid box contains a degree of uncertainty.

In the doubled CO_2 run, temperatures exhibited a tendency towards reduced variability from January through April for the four study areas. In addition, the researchers examined CO_2-induced changes in the northern hemisphere interannual temperature variability. The results from this investigation are striking:

> In the months for which the climate change shows a decrease in the latitudinal temperature gradient (September through May), the interannual variability for the Northern Hemisphere as a whole decreases in every month in the warmer climate. (Rind et al. 1989)

A reduction in interannual temperature variability associated with global warming has a plausible physical explanation. With global warming, the climate models predict greater warming at higher latitudes than at lower latitudes, thereby reducing the latitudinal temperature gradient. Reductions in this gradient will reduce the advection of cold and warm air masses which are a major cause of large temperature changes.

In the analysis of changes in precipitation, there was a positive correlation between the change in mean value of precipitation and the change in interannual variability. Variability increased in 31 of the 44 months in which there was a change in variability with the doubled CO_2 climate. The results were most pronounced in the Southeast, where variability increased for every month of the year.

Although there is no a priori reason to expect an increase in precipitation variability with an increasing mean value, such an expectation is not unreasonable. Higher temperatures will cause greater rates of evaporation, thereby stimulating the hydrologic cycle. For instance, it has been estimated that a doubling of atmospheric CO_2 will result in an 11% increase in global rainfall (Rind, 1988). Rind et al. (1989) conclude, "With all else the same, this [increase] should lead to increased variability." This depends, however, on exactly how the increase in global rainfall is expressed: more precipitation events or more intense precipitation. More intense events would cause greater variability at the time-scales of interest to flood managers, while longer-term (e.g., interannual) variability would be important to water supply planners.

It is important to keep in mind that climate modelers know much less about precipitation processes than temperature and that reliable predictions of precipitation changes are not yet available. Moreover, other important characteristics of the climate system, including regional patterns of temperature change and the general circulation, will not remain the same; hence, increases as well as decreases in precipitation variability around the earth could be the outcome of global warming.

An analysis of changes in daily variability of temperature and precipitation with increasing levels of CO_2 was also conducted. Temperature variability tended to decrease, although the changes were not statistically significant. Changes in daily variability of precipitation were consistent with the results of changes in interannual variability. That is, daily precipitation variability tended to increase when mean values of precipitation increased.

Finally, possible changes in the variability of the diurnal temperature cycle were examined. There was a strong tendency for this daily temperature range to decrease in the summer (in the other seasons, both increases and decreases occurred in the amplitude of the diurnal cycle). This is due to the dominance of radiative heating (due in part to generally light winds) in the summer compared to the other seasons. In the doubled CO_2 climate, cloud cover decreased at night in the winter, spring, and fall. There was little cloud cover change in the evenings for the summer months. An explanation is offered by the authors: "Additional CO_2 (and water vapor in the warmer climate) would act as greenhouse material in limiting radiative cooling at night, while leaving solar radiational heating during the day unaffected" (Rind et al., 1989).

This study represents one of the initial attempts to model changes in climate variability which will attend mean changes in temperature and precipitation. As such, the results provide only a rough approximation of possible changes in climatic variability in the 21st century (as witnessed by the number of caveats which the authors include in the study). However, the study's primary results--decreases in interannual temperature variability and extremes in daily temperature variability in winter and early spring, increases in precipitation variability (on both inter-annual and daily time scales), and a decrease in the range of the summer diurnal cycle--do have reasonable physical explanations. Such changes in variability, occurring in concert with changes in climatic means, will magnify the impacts of climate change on society. Increased precipitation variability, in particular, would be bothersome to water resource planning.

In another ongoing study by a group at NCAR in Boulder, Colorado, (Mearns et al., in preparation), comparisons are being made between GCM "control" and "perturbed" runs to examine how well the GCM can reproduce current climatic variability. Over-all, few such studies have been conducted, and the inability of GCMs to recreate current conditions of climatic variability is a major stumbling block in attempts to model climate variability under CO_2-perturbed conditions.

THE POTENTIAL WATER RESOURCE IMPACTS OF CLIMATE CHANGE

One of the most dramatic impacts resulting from global climatic change could be alteration in regional hydrologic conditions and subsequent changes in regional water availability, water quality, flood hazard, and other elements of water resources. Studies undertaken during the past decade to evaluate regional hydrologic implications of climatic change tend to indicate a high degree of sensitivity of regional hydrology to even small changes in precipitation and evapotranspiration. This section examines some of these recent studies, paying particular attention to their methods and their implications for water resource management.

Assessing Hydrologic Impacts of Climate Change

As in most areas of climate impact assessment (see, for example, Kates et al., 1985; and Riebsame, 1988a), evaluations of the potential water resource impacts of global warming rely on empirical and projective studies. Empirical studies of past climate fluctuations, especially dry spells, give the resource manager an idea of the climate sensitivity exhibited by a particular basin or water management system (Russell, Arey, and Kates, 1970). Most empirical studies examine system function under extreme events (floods and droughts) and not climate change per se, but the results of these studies can be re-examined for the insight they offer on how systems might handle cumulative change.

Projective studies involve translating the climate scenarios described earlier into water resource impacts by using extrapolation or modeling techniques (Schwartz, 1977; Beran, 1986). The studies described below take both empirical and modeling approaches.

Recent Studies

Nemec and Schaake (1982) used arbitrary increments (namely, temperature changes of $\pm1^{\circ}C$ and $+3^{\circ}C$ and precipitation variations of $\pm10\%$ and 25%) to study impacts of climatic fluctuations on selected watersheds. In addition to calculating subsequent changes in hydrologic characteristics, they also determined the reservoir sizes necessary to achieve a certain level of water supply reliability under different climatic changes. Their results for the arid Pease River basin in the southwestern U.S. (Figure 10), show that a 10% decrease in precipitation led to 150% to 200% increases in storage required to yield 20% of the mean annual runoff at a fixed level of reliability.

Revelle and Waggoner (1983) used the well-known Langbein relationships of mean annual runoff, precipitation, and temperature (Figure 11) to estimate the impacts of a $2^{\circ}C$ warming and 10% precipitation decrease in the western U.S. Their results suggest marked decreases in runoff. For example, a 10% reduction in precipitation resulted in decreases in runoff ranging from 12% to 50%, depending on the change in temperature and original mean precipitation. However, Karl and Riebsame (in press) conducted an empirical analysis of relative climate and runoff fluctuations in the U.S. and found evidence that the Langbein nomogram overstates the effect of temperature changes on runoff,

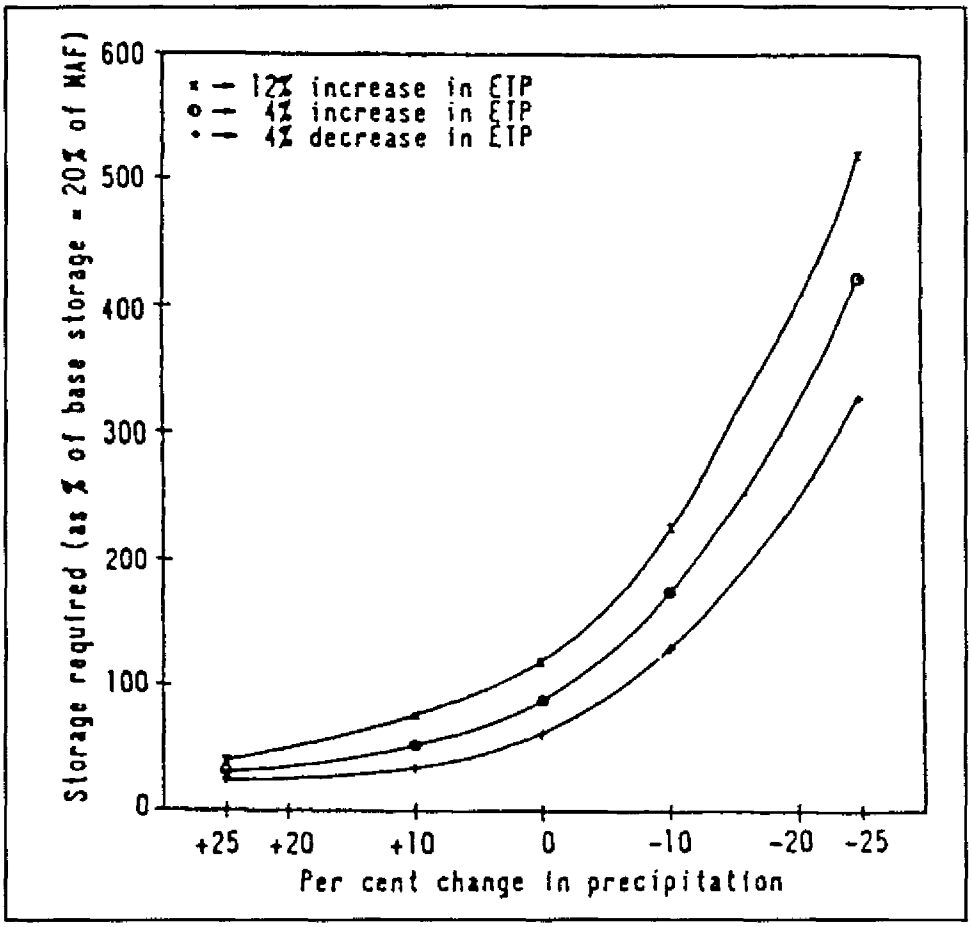

FIGURE 10

CHANGES IN RESERVOIR STORAGE NECESSARY TO PRODUCE A GUARANTEED YIELD AT A CONSTANT RELIABILITY AS A FUNCTION OF CHANGES IN PRECIPITATION AND POTENTIAL EVAPOTRANSPIRATION

Source: Nemec and Schaake, 1982

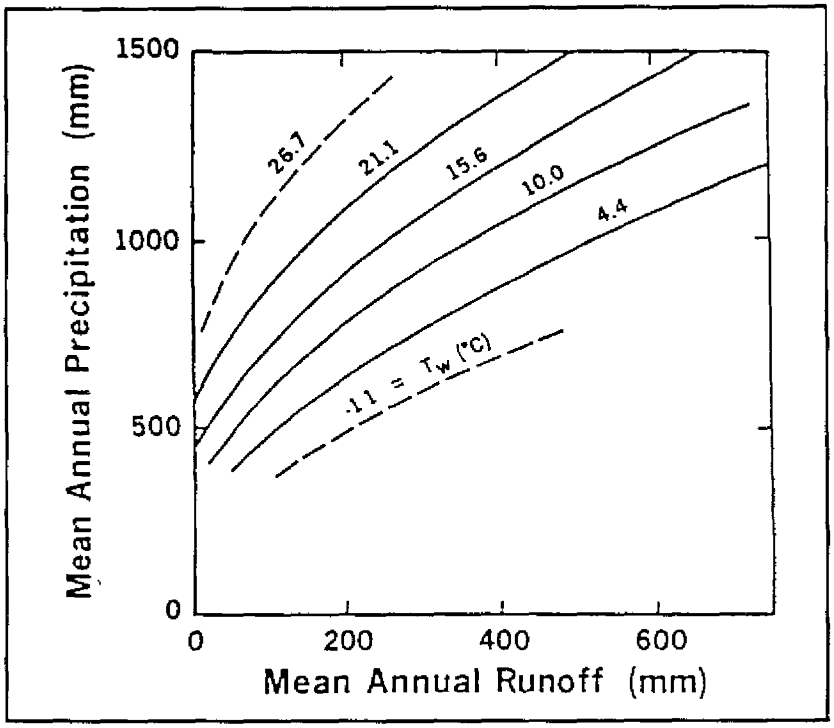

FIGURE 11

RELATIONSHIP BETWEEN MEAN ANNUAL PRECIPITATION AND RUNOFF AS A FUNCTION OF WEIGHTED MEAN TEMPERATURE (T_w)

Source: After Langbein, 1949

as illustrated by their version of the nomogram (Figure 12; see also, Wigley and Jones, 1985).

Cohen (1986) used output from two different GCMs--the GISS and GFDL models--to estimate future changes in water supply in the Great Lakes basin resulting from greenhouse-induced climate change. Runoff from the catchment area was computed for current and doubled CO_2 conditions. Changes in hydrologic parameters were calculated using the Canadian Climate Centre's version of the Thornthwaite water balance model. This empirical model

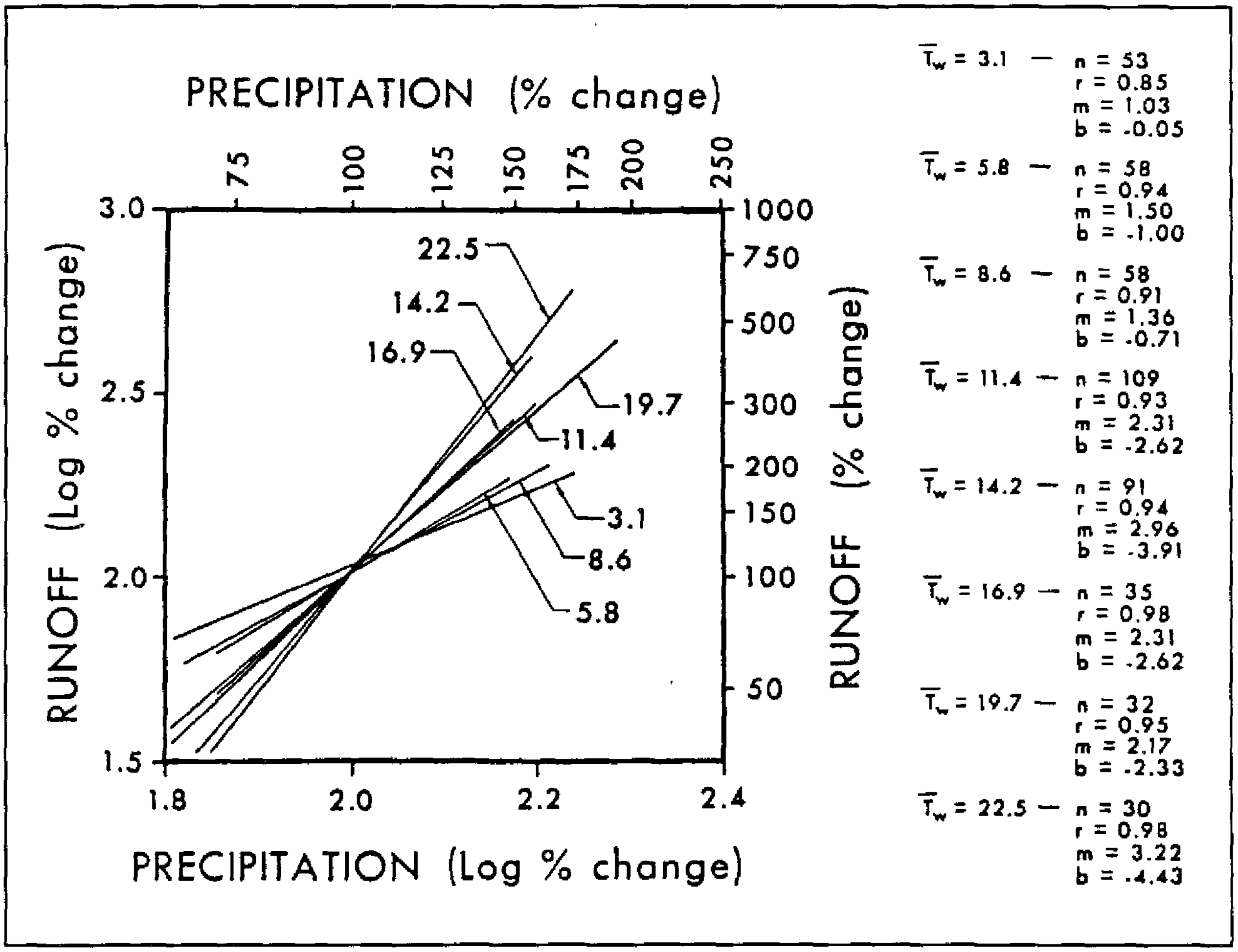

FIGURE 12

RELATIONSHIP BETWEEN EPOCH-TO-EPOCH CHANGES OF PRECIPITATION $(P_2/P_1)\%$ AND RUNOFF $(R_2/R_1)\%$ AS A FUNCTION OF T_w.

Source: Karl and Riebsame, in press

computes monthly mean evaporation based on latitude (a surrogate for insolation) and temperature.

Because 32% of the catchment area consists of lake surface, open water evaporation, which is greatly affected by wind speed, was of great importance. Consequently, a number of different scenarios (five) were used, matching the two model temperature patterns to alternative wind scenarios. Cohen cautions, however, that the large uncertainty regarding possible future wind characteristics over the lakes allows for only generalized conclusions about water resource impacts.

Cohen's results indicate a decrease in net basin supply under all five scenarios, as illustrated in Table 1. The differences between the two basic model scenarios are quite small; however, significant differences exist between the wind scenarios. GCMs predict greater warming at the poles than the equator, which would result in a decreased pole-equator temperature gradient and consequent decreases in pressure gradients and wind speeds. Hence, decreased wind speeds over the region are a plausible outcome of global warming, and Cohen postulated future speeds at 80% of current normals. This markedly reduced the water supply loss in a warmer climate (see Table 1).

TABLE 1

PRELIMINARY ESTIMATES OF NET BASIN SUPPLY (CMS)[a]

Source: Cohen, 1986

	Land based runoff +	Lake precip. −	Lake evap. =	NBS	Δ%
Normal[b]	5845	6224	4657	7412	--
GISS[b]	5368	6701	6199	5870	−20.8
GISS 80% winds[b]	5368	6701	4958	7111	− 4.1
GFDL[b]	5200	6168	5321	6047	−18.4
GFDL· 80% winds[b]	5200	6168	4256	7112	− 4.0
GFDL. GFDL winds[b]	5200	6168	5105	6264	−15.5
Cornwall (1959−1982)	−		−	7190	-

[a] Numbers may not add due to rounding errors
[b] Consumptive use not included

Cohen also suggested an integrated framework (Figure 13) for modeling the cascading impacts of climate variation on a region's water supply. Such a framework illustrates the vast array of components which need to be considered in comprehensive research on this topic; it can serve as a guide to other comprehensive basin studies.

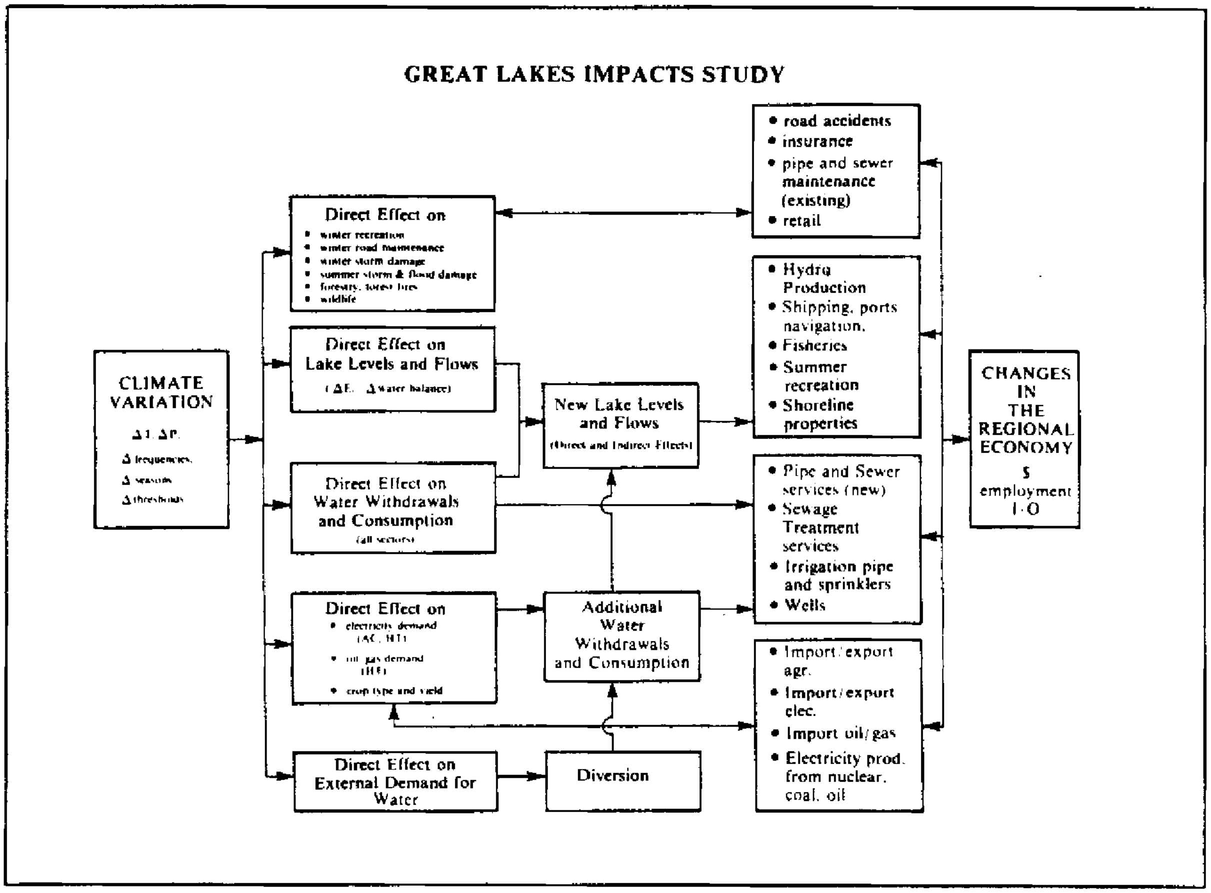

FIGURE 13

FLOW CHART OF THE COMPONENTS OF CLIMATE IMPACTS AND RESPONSES IN THE GREAT LAKES REGION OF NORTH AMERICA

Source: Cohen, 1986

Gleick (1987a, 1987b) evaluated the impacts of climate change on the hydrological characteristics of California's Sacramento River basin. This basin was selected because of the importance of its runoff to agriculture and industry, as well as the good quality and quantity of available hydrologic data. However, even with this relative wealth of pertinent data, Gleick cautions that hydrologic impacts of climatic change cannot be predicted with certainty sufficient to change current management operations.

Gleick used both GCM data and arbitrary increments to provide input to a modified version of the Sacramento water-balance model (modified, that is, for use under conditions of changing climate). Eighteen different climatic scenarios were created: ten hypothetical scenarios involving combinations of +2°C and +4°C, and ±0%, 10%, and 20% precipitation; and eight scenarios of GCM-predicted temperature and precipitation changes from the GFDL, GISS, and NCAR models. Output from the GCMs was in the form of temperature and precipitation data for current and doubled CO_2.

The most important changes noted by Gleick in this study were: 1) persistent decreases in summer soil moisture, 2) decreases in the magnitude of summer runoff, and 3) increases in the magnitude of winter or early spring runoff. Because of the region's Mediterranean climatic regime (i.e., most of the precipitation occurs in the winter months, followed by a summer drought), water resource managers are strongly dependent on spring runoff, much of it from snowmelt, to fill reservoirs in order to meet high summer demand. Thus, more peaked spring runoff would logically require more storage capacity even with no change in total runoff.

Gleick created a "two-basin model" in order to better estimate the magnitude and timing of runoff in the Sacramento basin because of the heterogeneity of the basin's physical character. He split the basin roughly into two hydrologic areas: the lowlands of the Central Valley and the mountains of the Sierra Nevada. A large percentage of runoff in this basin is from snowmelt and a "one-basin model" cannot accurately show how the timing of snowmelt might change in response to climate change. In comparison with the one-basin model, the two-basin model more accurately reproduced both timing and magnitude of monthly runoff conditions. As a result, the model shows promise for the evaluation of the impact of climatic changes on regional hydrologic characteristics. However, changes in initial climate conditions may necessitate changes in how the model is divided, in turn affecting its accuracy.

The U.S. Environmental Protection Agency's national assessment of climate change impacts (at this writing the full report to Congress is still in draft form; see Smith and Tirpack, in press) includes hydrological aspects chiefly in the California and Great Lakes case studies. The California study will be discussed here.

Lettenmaier and Gan (1988) studied the potential hydrologic impacts of global climate change on four catchments in California's Sacramento-San Joaquin Basin. The four basins were chosen on the basis of geographic and hydrologic diversity, the absence of upstream flow regulation, and the availability of long-term hydrological and meteorological data.

Two different hydrologic models--one for prediction of snow accumulation and ablation, another for soil moisture accounting--were used to simulate daily outflows from each of the four watersheds. The models were used to simulate hydrologic conditions under seven different climatic scenarios.

The warming associated with all the climatic scenarios resulted in a consensus among the models on a dramatic shift in the snow accumulation pattern in each of the basins:

> under the warmer conditions predicted by the GCMs, snow would occur only rarely at lower elevations, and the snow accumulation would be reduced at the higher elevations.

The models also indicated a shift of the maximum mean runoff from the spring to winter. As in Gleick's study of the entire Sacramento Basin, winter runoff increased, while spring and summer runoff (and, consequently, soil moisture) were greatly reduced. A shift in maximum evapotranspiration to earlier in the season was also noted. Simulated changes in annual runoff totals were minor and generally regarded as inconsequential. As the authors stated,

> From a hydrologic perspective, GCM-predicted changes in precipitation, for which there is less consensus than temperature, would be less important than the predicted temperature changes.

Sheer (1988) used a water balance model (developed by Water Resources Management Inc. for use by the Metropolitan Water District of Southern California) to simulate the effects of possible future climate change on deliveries of California's two largest water systems--the federal Central Valley Project (CVP) and the California State Water Project (SWP).

The GISS, GFDL, and OSU models were used to create doubled CO_2 climate scenarios, in addition to base runs (representative of current climate), that were then used as input to the water balance simulations. Although outputs of the GCMs differed (the run using the OSU model showed a smaller change from the base run than the other two GCMs, for instance), impacts of the three scenarios were roughly similar. Increased temperatures in all three doubled CO_2 runs resulted in more winter precipitation falling as rain, thus reducing the winter snowpack. Higher temperatures also lead to earlier winter snowmelt. Thus, instead of the snowpack acting as storage for use in the irrigation season, much of it would melt earlier and run "unused" to the sea. This would represent a decrease in water which could be reliably supplied by either the Central Valley Project (CVP) or the State Water Project (SWP).

All models showed little change in reservoir storage at the end of March, i.e., the end of the shortened runoff season (only the levels of Oroville Reservoir, the largest storage facility of the SWP, were modeled), because reservoir levels are limited by the need to preserve free volume for flood control. However, <u>all</u>

three models concur that reservoir storage at the end of May would be substantially lower, because of the quicker snowpack melt in the spring brought on by warmer temperatures.

Although the models predict a change in runoff seasonality (i.e., more runoff in the winter months but less in the summer), they also show an increase in total annual outflow. Such an increase may partially offset the "loss" of runoff resulting from earlier snowmelt (runoff which cannot be stored). However, from a water management perspective, the change in runoff seasonality is the more significant factor and would overshadow small changes in annual totals. These results indicate that even climatic shifts that increase moisture may cause serious water management problems in finely tuned systems like California's SWP and CVP.

Climate Change and Water Resource Systems

Most water projects are designed for both flood and supply management, and involve planning horizons of several decades, within the time frame of potentially large global warming effects (Schwartz 1977; Cohen 1986). Water project planning is predicated on expected hydrological conditions based on data from the past 30 to 100 years. Thus potential global warming raises the question of how well water projects based on historical conditions will handle future climate change. Fortunately, most projects incorporate substantial buffering capacity. Hanchey et al. (1988) argued that project planners had

> over the course of fifty years of application and refinement [developed] a large body of empirical and theoretical procedures and decision rules that have yielded what are generally considered to be fairly

> robust and resilient project designs. . . . This empirical approach, emphasizing as it does extremes of climate variability over the past 100 years, encompasses a significant proportion of the anticipated [climate] changes, at least for large scale water management. (p. 399)

The fact remains, however: climate change is, by definition, a change in the statistical properties of climatic elements on which project designs are based, and, depending on the size of safety margins, it will change the frequency of conditions that approach or surpass failure thresholds. Assuming that planners have achieved socially acceptable project reliability, then any climate change larger than the uncertainty inherent to hydro-climatological analysis violates explicit and implicit planning criteria.

Without project sensitivity analyses linked to climate change projections, we cannot know how significant this violation may be. Assumed climate stability is a potentially dangerous "blind spot" in water project design, given the threat of global warming (Lettenmaier and Burgess, 1978; Changnon, 1984). Assessments of the vulnerability of water projects to climate change are rare, and beyond a reassuring sense that such systems have been designed in a conservative manner, the capacity of most existing projects to accommodate climate change is unknown.

Water projects can be adjusted to climate change by altering project goals (for example, accepting lower reliability), operations, or physical facilities. Goal and operational changes are common in a project's lifetime, but such changes tend to be made only when droughts or floods cause near or actual system failure (Glantz, 1982; Rhodes et al., 1984; Phillips and Jordan, 1986; Riebsame, 1988b). Physical facility changes due to altered environmental conditions are much less common, though precedents are being set where postconstruction studies have revealed geological risks to dams and other control structures.

In summary, it appears that even relatively small changes, such as those that might occur in the next one to two decades, can disrupt water systems. Further climate change, now projected to occur at rates unprecedented in human history, can only exacerbate the problem. The problem for the water resource planner is to decide when and how to respond to the threat, given its potential consequences and great uncertainties. The long lead times associated with water resources planning, and the assumption in most hydrological analyses that climate characteristics are stationary over time, exacerbate this decision-making problem. While it may not yet be time to act, it is clearly time to assess sensitivities and canvass possible responses.

CONCLUSIONS

The material presented here shows both strengths and weaknesses in our understanding of climate change. The general effect of growing greenhouse gas concentrations in the atmosphere is well understood and accepted almost universally: there will be a warmer global climate. But the specifics of timing, rate, and regional magnitude and character of likely climate changes are not yet within our grasp. Nevertheless, the growing credibility of global warming predictions, and growing public and policy maker awareness, means, simply, that water resource managers will come under increasing pressure to respond in anticipation of climate change, even before the uncertainties are significantly reduced. How they respond to this pressure is another issue.

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APPENDIX: A BRIEF ANNOTATED BIBLIOGRAPHY OF CLIMATE AND WATER RESEARCH

Beran, Max
1986 "The Water Resource Impact of Future Climate Change and Variability." In James G. Titus, ed., Effects of Changes in Stratospheric Ozone and Global Climate: Volume I. Washington, D.C.: U.S. Environmental Protection Agency.

This paper describes methods and models that have been used by hydrologists to forecast the effects of climatic change on water availability for uses such as irrigation, hydropower generation, and human consumption. The paper consists mainly of a survey of literature on both the hydrological and water resource impacts of climate change. A distinction between the two is drawn--hydrology being concerned with physical processes such as interception, runoff, and infiltration; water resources generally referring to the management of water available at the place and time required, in acceptable quality and quantity.

Beran also points to the relatively small amount of research that has been conducted on the impacts of climatic change on hydrology and water resources. Future research topics are suggested, and international organizations such as the World Meteorological Organization (WMO) and United Nations Environmental Programme (UNEP) are proposed as appropriate agencies to oversee this future research.

Changnon, Stanley A. Jr.
1977 "Climatic Change and Potential Impacts on Water Resources." In Living with Climatic Change, Phase II. McLean Virginia: Mitre Corp.

The impact of changing levels of precipitation on runoff is examined. It is shown that changes in precipitation amounts are magnified in the resulting changes in runoff. The implications of changes of lake levels in the Great lakes area (resulting from changing amounts of precipitation) for sectors of the regional economy are also explored. Due to benefits which would be enjoyed by the regional hydropower and navigation interests, a small (10-20%) increase in fall precipitation would result in a net benefit to the regional economy ($0.6--$1 million annually, in 1977 dollars). It is also suggested that decreases in precipitation would clearly result in sizeable economic "disbenefits."

The effects of urbanization on local meteorological and hydrological characteristics are also studied. An important change noted is an increase in the frequency of intense, short-duration rainfall events. An investigation of the impacts of additional urban-related summer rainfall on water quality suggests that streamwater quality is reduced. It also appears that groundwater supplies may also be reduced in quality as a consequence of urban-induced precipitation increases.

Changnon, Stanley A., Jr.
1984 "Misconceptions About Climate in Water Management." Pages 1-8 in Water Resources Center, eds., Proceedings of Conference on Management Techniques for Water and Related Resources. Champaign-Urbana: University of Illinois.

In this paper, Changnon discusses areas of climate uncertainty which relate to water and its management. The notion of long-term climatic stability is refuted. The terms "average" and "normals" are sometimes used in hydrology with the belief that although climate fluctuates on an interannual basis, it has a long-term stability. Changnon points out, however, that the climate system is in a constant flux with varying periods (i.e., warmer or colder and wetter or drier) lasting from five years up to thousands of years. A critical aspect of climate change with regard to water management--changes in the frequency and magnitude of extreme events--is examined, as well. Climate change induced by human activities is also discussed. Due to the great deal of scientific uncertainty associated with such changes, it is suggested that effects attributed to large-scale climate changes (i.e., continental, hemispheric, or global) are misconceptions. Finally, recent research on climate and water management conducted by the Illinois State Water Survey is described.

Dracup, J.A.
1977 "Impacts on the Colorado River Basin and Southwest Water Supply." In National Research Council, eds., Climate, Climatic Change, and Water Supply. Washington D.C.: National Academy of Sciences

The Colorado River basin has more water exported from it than any other U.S. river basin and dominates the water resources of the Southwest. Dracup describes the legal framework governing allocation among its many users. Most of these allocation policies were established in the 1920s, a period of exceptionally high precipitation and runoff in the basin. Hence, the waters of the Colorado are often characterized as overallocated. This fact, coupled with increasing water demands in the basin, make the possibility of climatic change ominous. Possible future demands, several possibilities of augmenting the river's flow, and potential impacts of a future drought in the basin are briefly discussed.

Glantz, M.H., and T.M.L. Wigley
1986 "Climatic Variations and Their Effects on Water Resources." Page 625-641 in D.J. McLaren and B.J. Skinner, eds., Resources and World Development. New York: Wiley and Sons.

Climate variability and change will have impacts on both water resource supply and demand; however, this paper examines only effects on supply. Although both precipitation and evapotranspiration are important factors in the response of the hydrologic cycle to climatic fluctuation or change, precipitation is by far the most important. One of the authors' main findings is that both precipitation and evapotranspiration can be magnified into larger changes in runoff, especially in areas with low runoff ratios. Hence, arid and semiarid zones are particularly sensitive to climatic variability. Three case studies in which existing climatic data were incorrectly used are also presented.

Gleick, Peter H.
1988 "The Effects of Future Climatic Changes on International Water Resources: The Colorado River, the U.S., and Mexico." Policy Sciences 21: 23-39.

Conflicts over international waters have been increasing in recent decades and will likely increase in frequency and intensity as future climatic changes alter the quality and/or availability of water resources. Unless agreements which allow for climatic changes in international water treaties can be implemented, international tensions in general could increase. The region which perhaps best exemplifies this type of potential political conflict in North America is the Colorado River basin of the United States and Mexico. Although past disagreements between the two countries over the waters of the Colorado have been largely resolved, changes in the Colorado's hydrologic regime could quickly revive such differences. Hydrologic changes would also exacerbate the intense competition for water from the Colorado within the U.S. This paper examines the possible political conflicts that might arise as a result of climatic changes. Recommendations for incorporating the issue of climatic change into international agreements are also put forth.

Karl, Thomas R. and William E. Riebsame
(in press) "The Impact of Decadal Fluctuations in Mean Precipitation and Temperature on Runoff: A Sensitivity Study Over the United States." Climatic Change.

The nature of climate variability is such that decadal fluctuations in average temperature (up to 1°C annually or 2°C seasonally) and precipitation (approximately 10% annually), have occurred in most areas of the United States during the modern climate record (the last 60 years). The impact of these fluctuations on runoff is investigated, using data from 82 streams across the United States that had minimal human interference in natural flows. The effects of recent temperature fluctuations on streamflow are minimal, but the impact of relatively small fluctuations in precipitation (about 10%) are often amplified by a factor of two or more, depending on basin and climate characteristics. This result is particularly significant with respect to predicted changes in temperature due to the greenhouse effect. It appears that without reliable predictions of precipitation changes across drainage basins, little confidence can be placed in hypothesized effects of the warming on annual runoff.

Klemes, V.
1985 Sensitivity of Water Resource Systems to Climate Variations. World Climate Program Publication #98. Geneva: World Meteorological Organization.

This paper reviews a project which examined the sensitivity of water resource systems to variations in climate. The project was conducted by the World Climate Programme (WCP), a branch of the World Meteorological Organization (WMO). The project concentrated on two areas: simulation of changes in hydrologic parameters corresponding to climatic changes, and evaluation of the performance characteristics and design parameters of water-resource systems for the hydrologic regime simulated from changes in climate.

Two river basins in the U.S. were selected for the study: the Leaf River basin of Mississippi, located in a humid region, and the Pease River basin of north-central Texas, located in an arid region.

An important finding of the hydrologic impact analysis was that in the humid Leaf River basin, the percentage of runoff change was two-to-three times larger (depending on changes in evapotranspiration) than the runoff change. However, such a change in the arid Pease River basin was five-to-eight times as large.

A discussion on aspects and weaknesses of hydrological models, especially with regard to their ability to model changes in runoff resulting from changes in climate, is also included. Recommendations for improvements in hydrological modeling are given. The paper concludes with five studies, all regarding climatic variations and their impacts on hydrological-water resource systems.

Matalas, N.C. and M.B. Fiering
1977 "Water-Resource Systems Planning." Pages 99-111 in Climate, Climatic Change and Water Supply. Washington, D.C.: National Academy of Sciences.

The business of planning and designing water resource systems is subject to uncertainties imposed by the stochastic nature of climate and streamflow. In this paper, concepts of robustness, regret, and resilience are introduced as indicators of a system's ability to perform adequately in the event of climatic change. The authors also discuss some of the engineering, economic, and political considerations which contribute to the design selection process. Paretian analysis is presented as a potentially useful method for resolving conflicts of interest among groups with differing values in regard to project goals and different risk aversion characteristics. Matalas and Fiering emphasize that nontechnological factors, including political, institutional, military, social and other issues, can be pivotal in determining the course in the design process.

Novaky, Bela, C. Pachner, K. Szesztay, and D. Miller
1985 "Water Resources." In R.W. Kates, J. Ausubel, and M. Berberian, eds., SCOPE 27, Climate Impact Assessment. New York: John Wiley and Sons.

In this chapter from the SCOPE volume on climatic impact assessment, the authors describe the many ways in which climatic fluctuations might alter the water resources of a river basin, region, or nation. In addition to addressing impacts over this spatial range, the temporal variety of climatic fluctuations and the correspondingly diverse impacts (e.g., soil moisture and storm flow on short time scales, and groundwater and base flow on longer time scales) is discussed.

The authors put forth major reasons why assessments of water-related climatic impacts are needed, and suggest lines along which such assessments might proceed. A section examining the "climate-water resources-water management-society" pathway is followed by a section which examines the elements of the "water resources-water management-society and economy" sequence. Finally, aspects of assessment integrated over this entire sequence are addressed.

Phillips, D.H. and D. Jordan
1986 "The Declining Role of Historical Data in Reservoir Management and Operations." Pages 83-88 in Proceedings of the Conference on Climate and Water Management. Boston: American Meteorological Society.

This paper examines the problems associated with the operation of Arizona's Salt River Project (SRP) in the face of growing urbanization and the attendant need to minimize flood damage. Historically, the primary function of the SRP has been storage; however, the present-day need to also provide flood control has decreased flexibility of reservoir operations. Recent studies which have updated the hydrometeorological records of the Salt and Verde River watershed (which provides roughly two-thirds of SRP supply) yielded dramatic results: the probable maximum floods on each river were recalculated to be several times larger than estimates used in original dam design. Phillips and Jordan point out that such climatologically derived statistics do not adequately address complex management problems, such as balancing water conservation against concerns of dam safety and mitigation of downstream flood damages. The authors go on to discuss advances made in methods for long-term forecasting and planning, such as the modeling of seasonal runoff and demand, as well as long-range weather forecasting.

Revelle, R.R. and P.E. Waggoner
1983 "Effects of a CO_2-Induced Climate Change on Water Supplies in the Western U.S." In Carbon Dioxide Assessment Committee, ed., <u>Changing Climate</u>. Washington, D.C.: National Academy Press.

Empirically-derived relationships between mean annual precipitation, temperature, and runoff are used to predict the impacts of a CO_2-induced climate change on water supplies in seven western U.S. watersheds. The authors assume a change--a "convenient increment"--of a 2°C increase in temperature and a 10% decrease in precipitation. Impacts on the Colorado River basin are emphasized due to its preeminence in the region. The authors point out that the 30-year or longer planning and construction horizon for major water projects normally proceeds under an assumption of climatic stability which is being challenged by a growing body of scientific evidence. It is suggested that the possibility of a CO_2-induced climate change should be accounted for in planning processes.

Riebsame, William E.
1988 "Adjusting Water Resources Management to Climate Change." <u>Climatic Change</u> 13: 69-97.

Some of the factors which hinder smooth adjustment to climatic change are highlighted. Among them are assumptions of long-term climatic stability and increasing environmental and economic constraints which inhibit the traditional strategy of using over-sized storage, thereby creating a comfortable "buffer" between supply and demand.

A case study of water resource managers' possible response to

climatic change in the Sacramento basin is presented. Increases in precipitation variability in the basin in the last 10-15 years illuminate possible problems water managers may face in adjusting to long-term climatic change. This increasing variability effected a change in the state's water delivery policy (its "rule curve"), and drastically reduced the RDF (reservoir design flood) return interval of Folsom Dam, a facility of the federal Central Valley Project. The case study shows the interaction of changing climate sensitivity and climate fluctuation as systems mature, as well as the effect of growing constraints on traditional adjustments to climate stress.

Rind, D. and Lebedeff, S.
1984 Potential Climatic Impacts of Increasing Atmospheric CO_2 With Emphasis on Water Availability and Hydrology in the United States. Washington, D.C.: U.S. Environmental Protection Agency.

This report focuses specifically on possible shifts in a range of hydrologic conditions that would accompany a doubling of atmospheric carbon dioxide. The significance of this report is that it represents the initial attempt to provide detailed regional hydrologic effects that would attend a CO_2 doubling.

Output from the GISS GCM is used to simulate future climatic and hydrologic changes. These changes are forecast at the "grid cell" level of the GCM, in this case roughly 17,000 square miles. This resolution prompted the authors to attach an important caveat to their study: the simulated values for a grid cell are only averages and, due to factors such as diverse topography within a grid cell, conditions at a specific location within the cell may differ considerably from the average value for that cell. Findings of the study include:

- A general pattern of increased runoff over the northwestern and extreme southwestern portions of the continent (i.e., +20-60%). Some areas in the central and eastern U.S. recorded decreases of 15-20%.
- Small reductions in upper-level soil moisture for most areas, with a larger reduction in the extreme northeast.
- Roughly similar increases in both precipitation and evaporation--both increased 11% globally--for a doubled CO_2 world. In the U.S., the northern and western U.S. recorded the greatest increases for both these values, each showing increases of 15-20% or more.

Russell, C.S., D. Arey, and R.W. Kates
1970 Drought and Water Supply: Implications of the Massachusetts Experiences for Municipal Planning. Baltimore: Johns Hopkins University Press.

This volume presents an intensive field study of the water supply system during a record four-year drought in the state of Massachusetts utilizing questionnaires, public documents, intensive interview surveys of 48 communities, newspaper files, and several special studies. The book is divided into five parts: water supply and demand: the level of system adequacy; climatic variation, the level of shortage, and the nature of short-run adjustments; the economic impact of water shortage; a planning model for municipal water supply systems; and practical system planning.

Timmerman, Peter, and A.P. Grima
1985 Climate Impact Assessment in the Great Lakes Basin: Overview and Research Recommendations. Environmental Monograph #7. Toronto: Institute for Environmental Studies, University of Toronto.

This small volume contains an overview paper and a set of research recommendations for research on the potential impacts of CO_2-induced climate warming in the Great Lakes Basin. The book summarizes the proceedings of a Canadian Climate Program workshop held February 8-9, 1985 at Seneca College, King City, Ontario.

Wigley, T.M.L., and Jones, P.D.
1985 "Influences of Precipitation and Direct CO_2 Effects on Streamflow." Nature, 314 (14): 140-152.

Wigley and Jones examine changes in streamflow which would occur in response to changes in precipitation and direct CO_2 effects on vegetation. CO_2-induced changes in vegetation--the closing of plant stomata, a decrease in transpiration rate, and an increase in water use efficiency--could make more water available for runoff and greatly complicate the impact of precipitation changes on the hydrologic cycle. For instance, reduced plant evapotranspiration would tend to offset any CO_2-induced reductions in precipitation.

Runoff ratios--present-day runoff/streamflow divided by present-day precipitation--are compiled for 27 of the world's major rivers. Rivers with lower runoff ratios, which usually flow through arid regions, generally had values of 0.1 or less, indicating a high sensitivity of runoff to precipitation (and, to a lesser extent, evapotranspiration) changes. The converse applies to rivers in more humid regions. Typical values for rivers in temperate regions were roughly 0.4, while tropical rivers were assigned values of roughly 0.6.

In addition to compiling these runoff ratios, the "direct effects" (on vegetation) of CO_2 on basins possessing various runoff ratios were assessed. It was shown that those direct effects are magnified in river basins possessing small (i.e., less than 0.2) runoff ratios.

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