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.

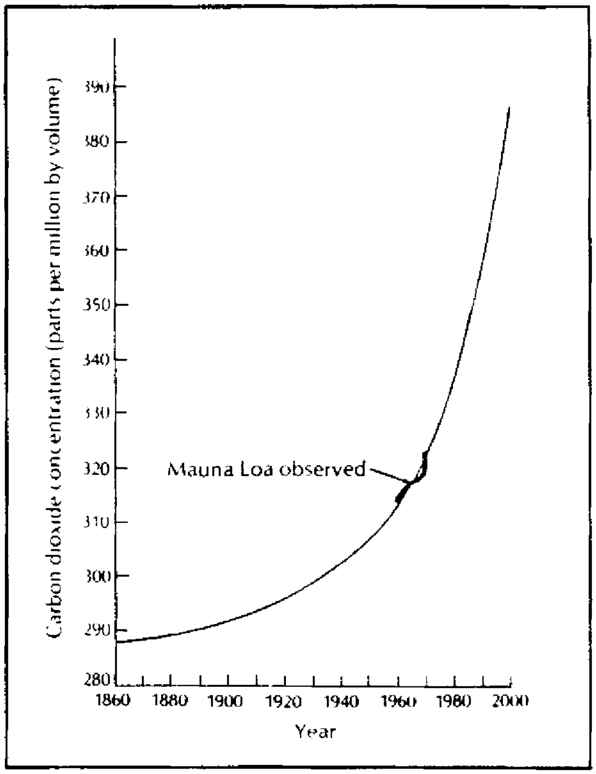


FIGURE 1

INCREASE OF CARBON DIOXIDE IN THE ATMOSPHERE SINCE 1860

Source. Anthes, 1981

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.

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

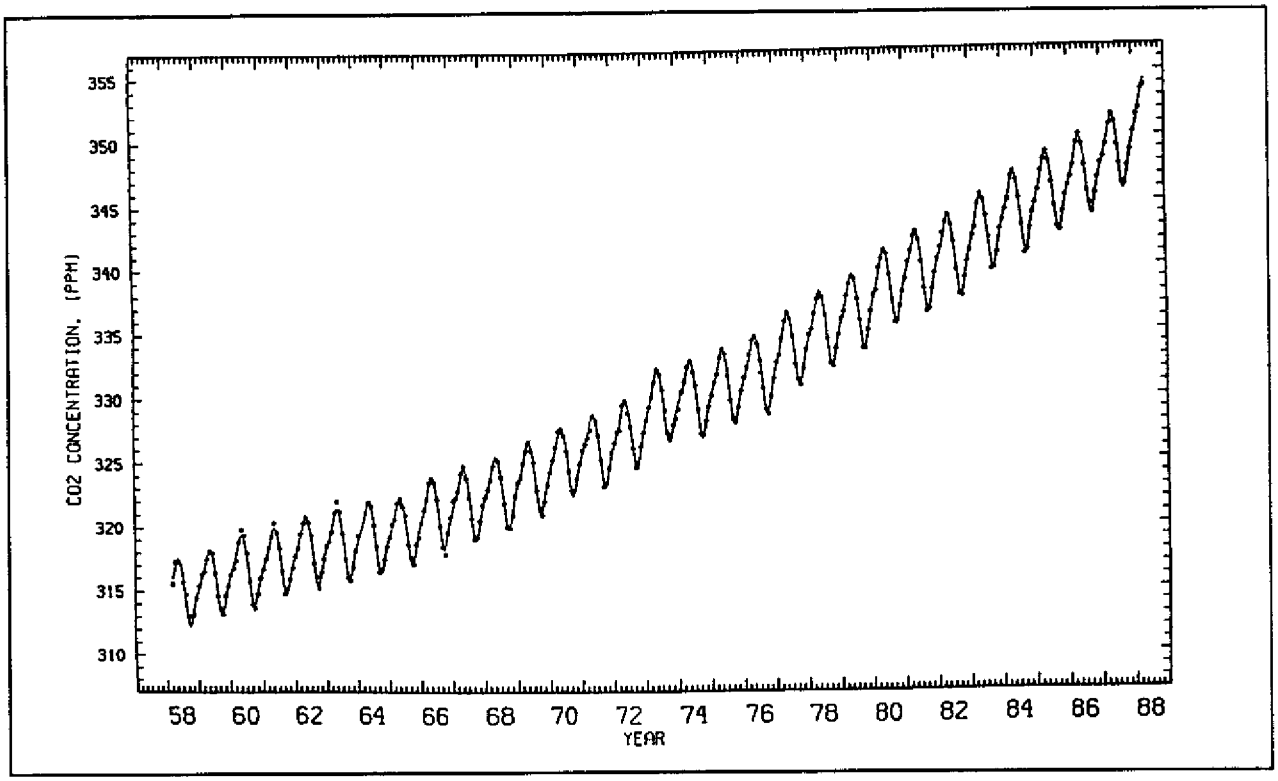


FIGURE 2

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°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

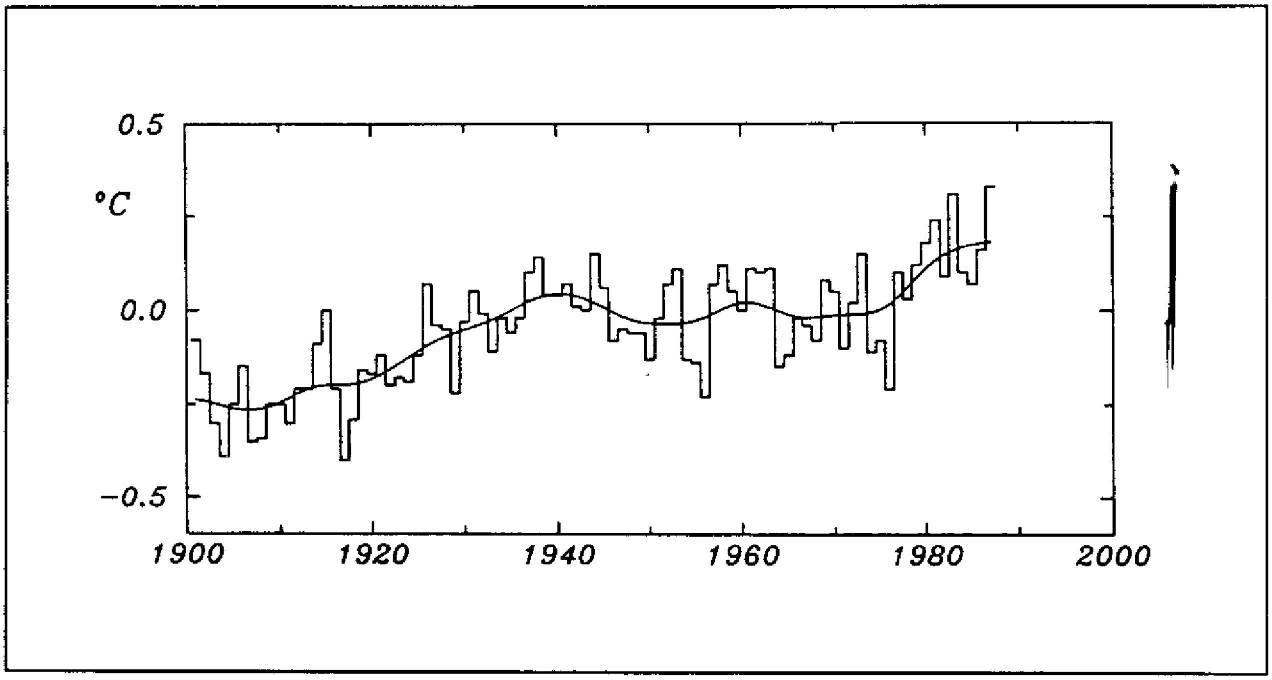


FIGURE 3

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)

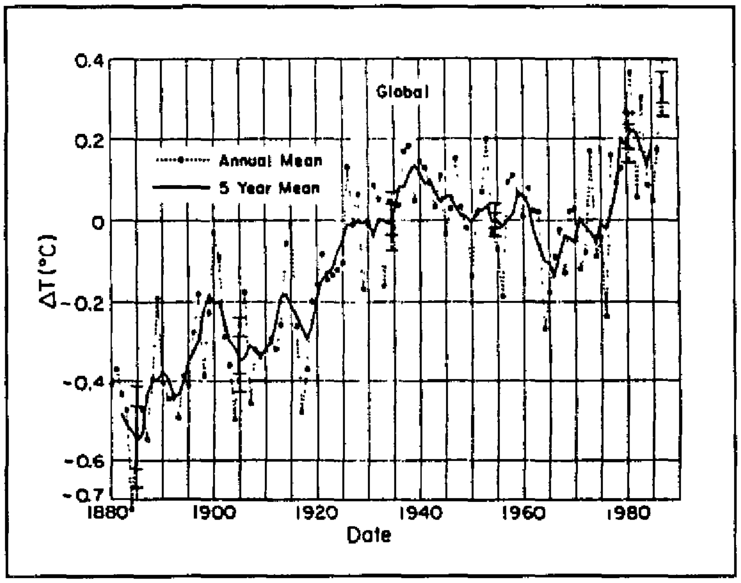


FIGURE 4

GLOBAL SURFACE AIR TEMPERATURE CHANGE

Source: 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.

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 ($2-3\sigma$). 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

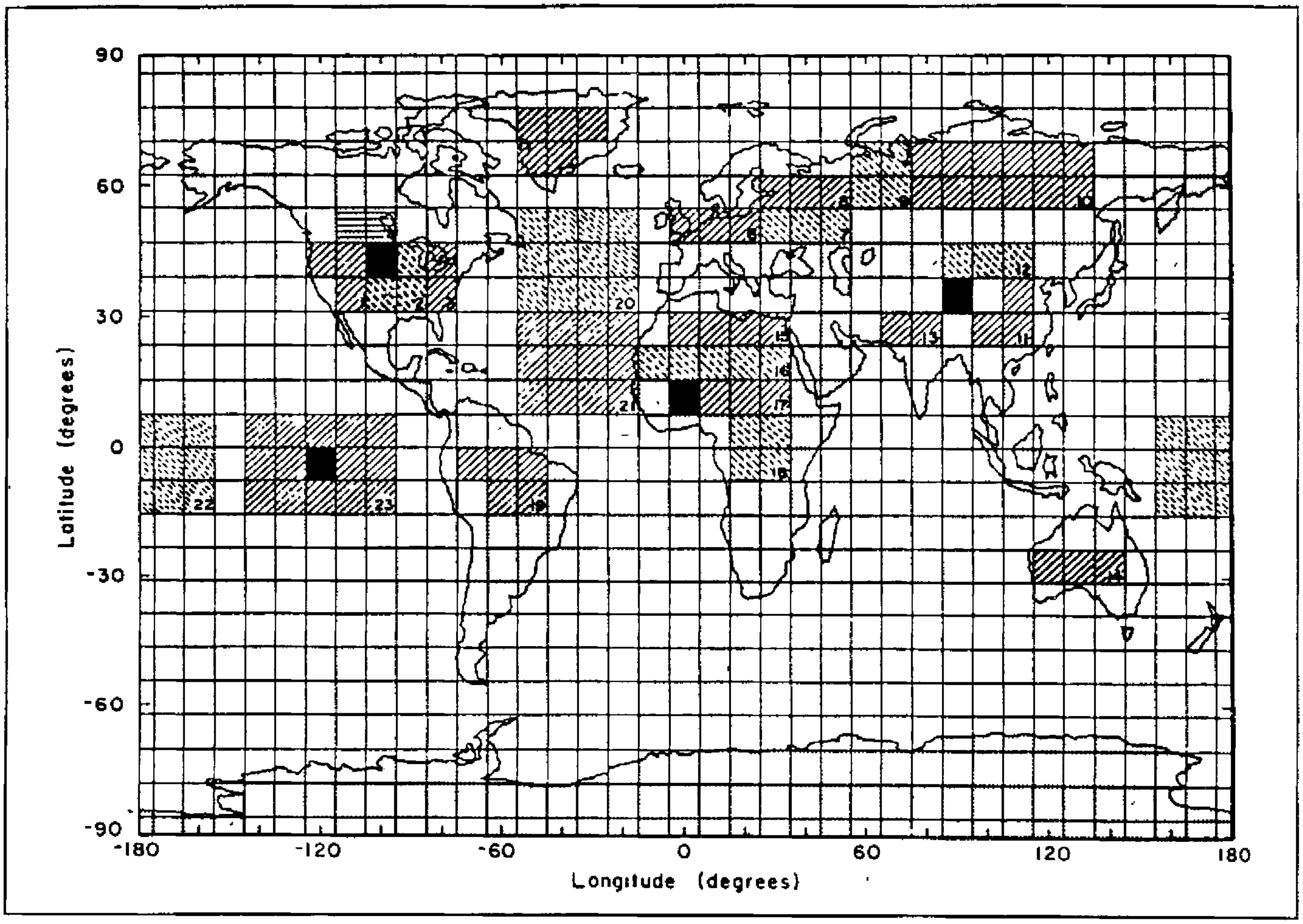
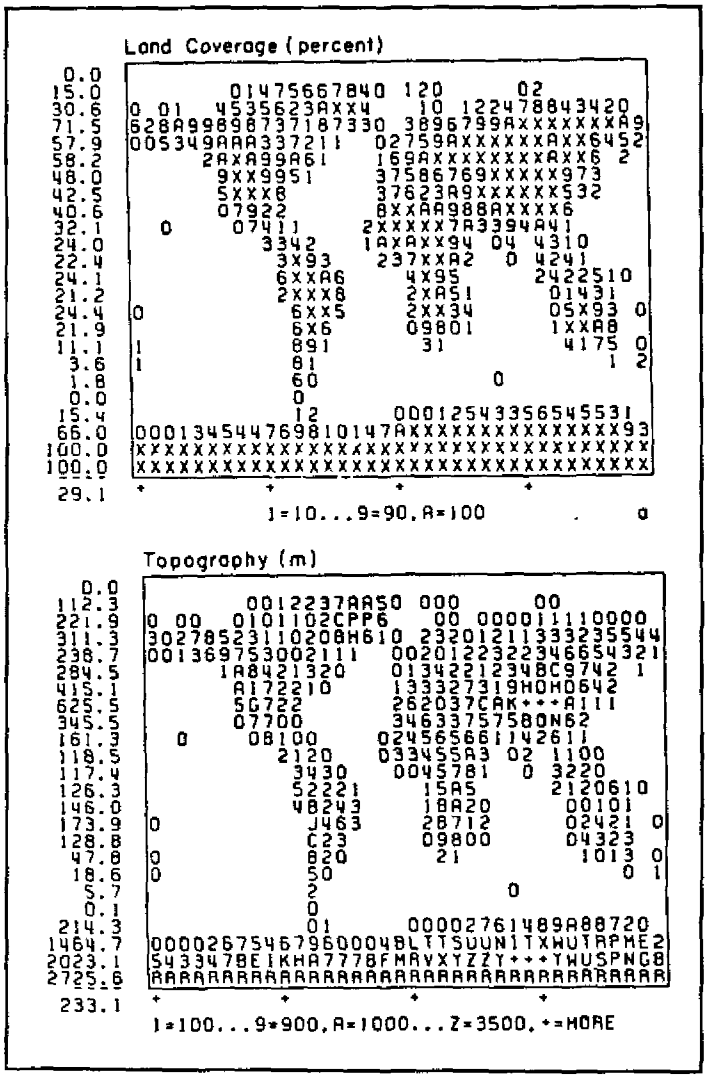


FIGURE 5

GRID SPACING FOR 8° BY 10° MODEL

(Shading indicates boxes for special study)

Source: Hansen et al., 1983



```
       Land Coverage (percent)
   0.0
  15.0        01475667840 120       02
  30.6  0 01  4535623AXX4   10  122478843420
  71.5  628A99898737187330 3896799AXXXXXXXA9
  57.9  005349AAA337211  02759AXXXXXXAXX6452
  58.2       2AXA99A61   169AXXXXXXXXAXX6 2
  48.0        9XX9951    37586769XXXXX973
  42.5        5XXX8      37623A9XXXXXX532
  40.6        07922      8XXAA988AXXXX6
  32.1    0    07411    2XXXXX7A3394A41
  24.0           3342   1AXAXX94 04 4310
  22.4            3X93   237XXA2  0 4241
  24.1            6XXA6    4X95     2422510
  21.2            2XXX8    2XAS1     01431
  24.4  0          6XX5    2XX34     05X93 0
  21.9             6X6     09801     1XXA8
  11.1  1          891      31        4175 0
   3.6  1          81                    1 2
   1.8             60            0
   0.0             0
  15.4             12     000125433565455 31
  66.0  0001345447698101 47AXXXXXXXXXXXXXXX93
 100.0  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.0  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  29.1  +        +        +        +
                 1=10...9=90,A=100      .    a

       Topography (m)
   0.0
 112.3        0012237AA50 000       00
 221.9  0 00  0101102CPP6   00  000011110000
 311.3  30278523110208H610 23201211333235544
 238.7  001369753002111  0020122322346654321
 284.5       1A8421320   01342212348C9742  1
 415.1        A172210    133327319H0H0642
 625.5        5G722      262037CAK+++A111
 345.5        07700      34633757580N62
 161.3    0    08100    024565661142611
 118.5           2120   033455A3 02 1100
 117.4            3430   0045781  0 3220
 126.3            52221    15A5     2120610
 146.0            48243    18A20     00101
 173.9  0          J463    28712     02421 0
 128.8             C23     09800     04323
  47.8  0          820      21        1013 0
  18.6  0          50                    0 1
   5.7             2             0
   0.1             0
 214.3             01     00002761489A88720
1464.7  000026754679600048LTTSUUN1TXHUTAPME2
2023.1  5433478EIKHA7778FMAVXYZZY+++YWUSPNG8
2725.6  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
 233.1  +        +        +        +
        1=100...9=900,A=1000...Z=3500,+=MORE
```

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.

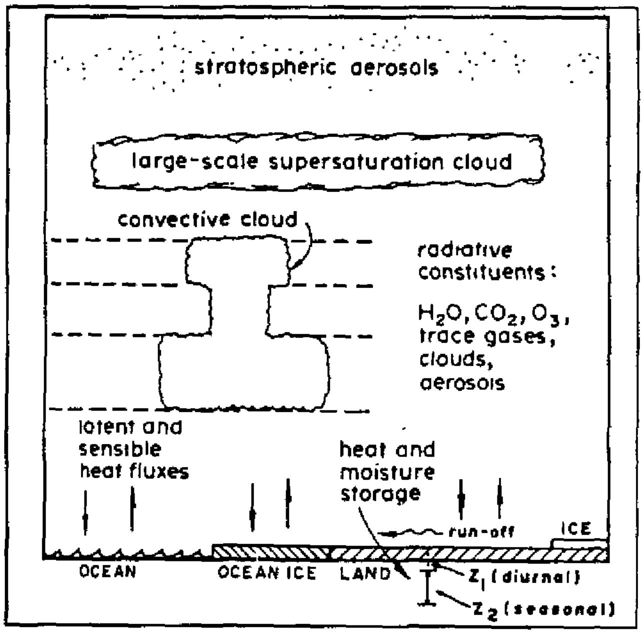


FIGURE 7

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.

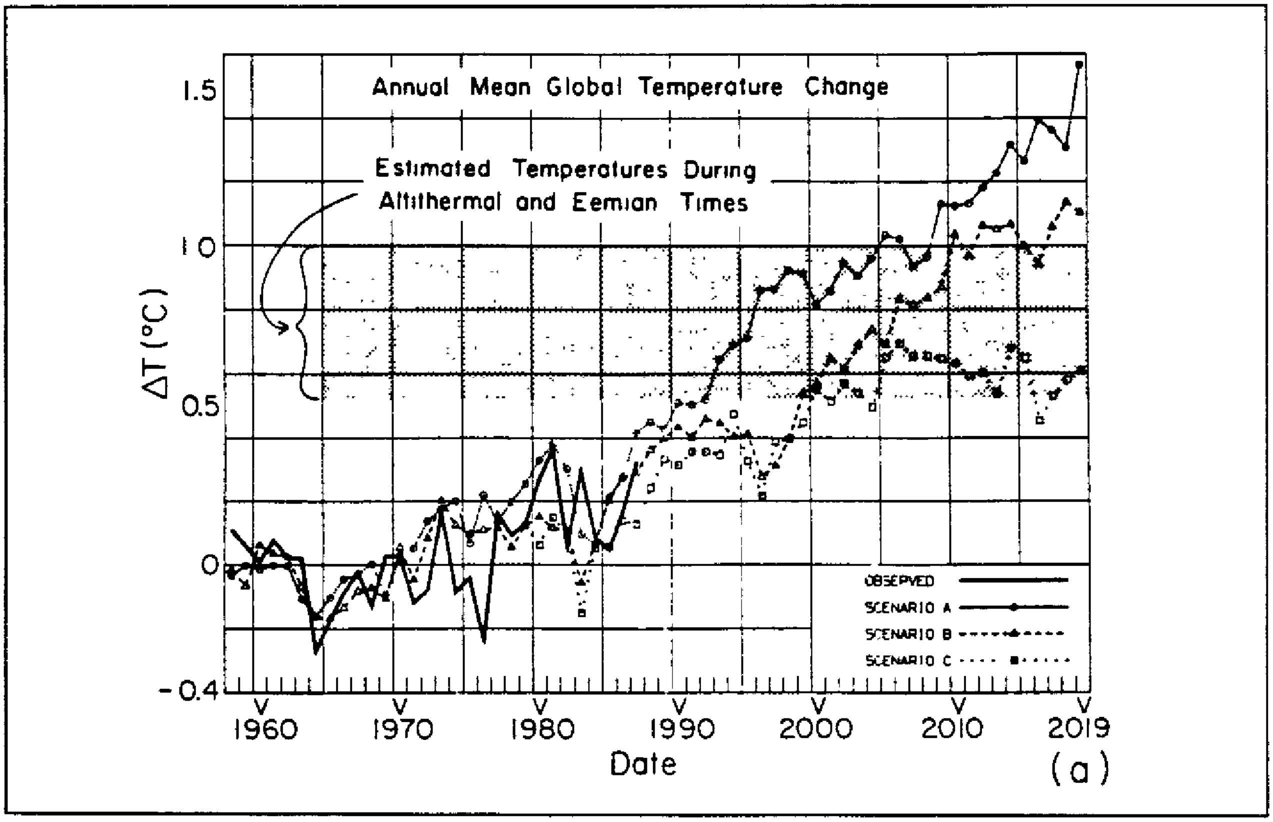


FIGURE 8

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 $0.13^{\circ}C$; hence, a warming of only about $0.4^{\circ}C$ 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,

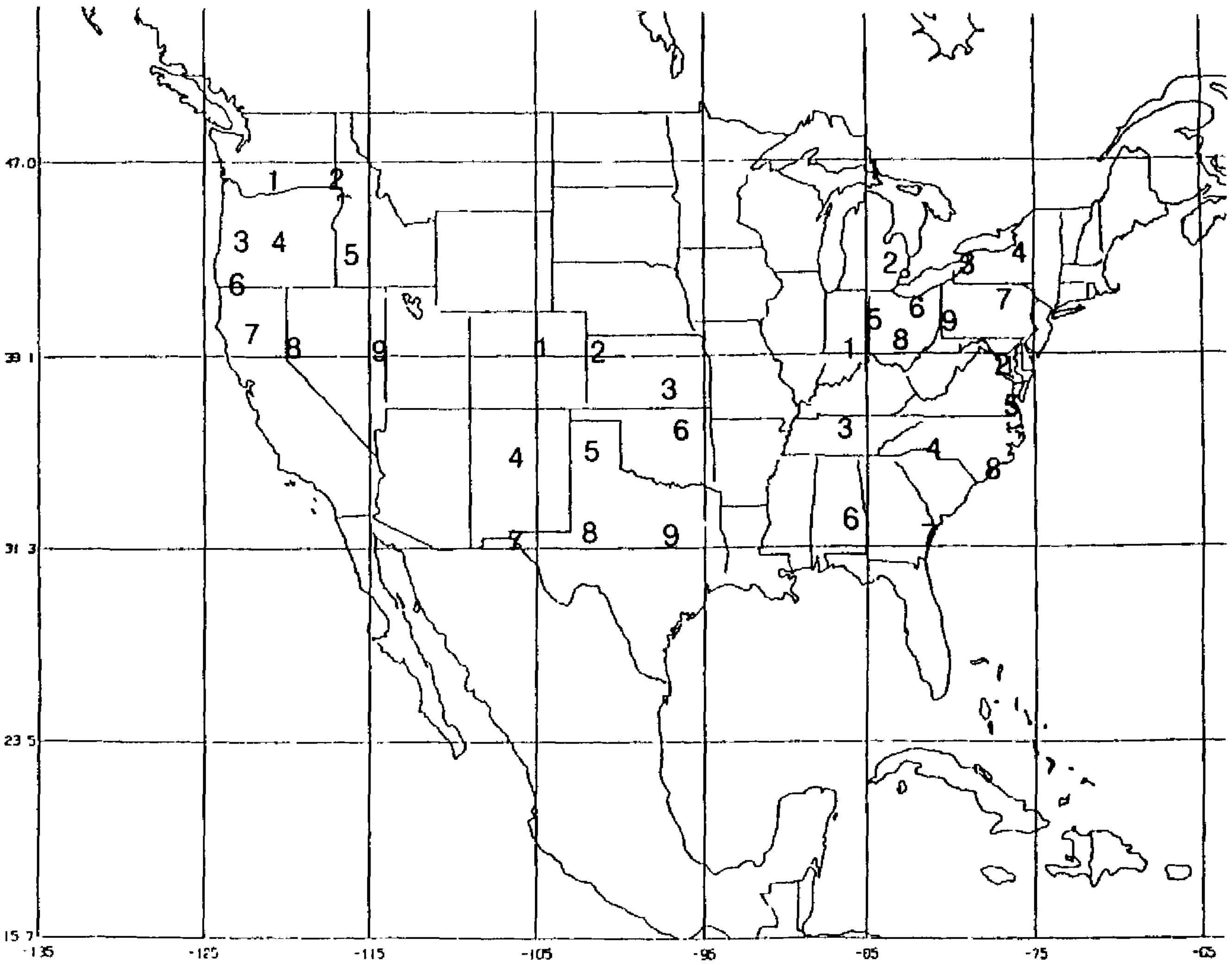


FIGURE 9

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 interannual 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. Overall, 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.