USE OF GENERAL CIRCULATION MODEL OUTPUT IN THE CREATION OF CLIMATE CHANGE SCENARIOS FOR IMPACT ANALYSIS*

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Abstract. Many scientific studies warn of a rapid global climate change during the next century. These changes are understood with much less certainty on a regional scale than on a global scale, but effects on ecosystems and society will occur at local and regional scales. Consequently, in order to study the true impacts of climate change, regional scenarios of future climate are needed. One of the most important sources of information for creating scenarios is the output from general circulation models (GCMs) of the climate system. However, current state-of-the-art GCMs are unable to simulate accurately even the current seasonal cycle of climate on a regional basis. Thus the simple technique of adding the difference between $2 \times CO_2$ and $1 \times CO_2$ GCM simulations to current climatic time series cannot produce scenarios with appropriate spatial and temporal details without corrections for model deficiencies.

In this study a technique is developed to allow the information from GCM simulations to be used, while accommodating for the deficiencies. GCM output is combined with knowledge of the regional climate to produce scenarios of the equilibrium climate response to a doubling of the atmospheric CO_2 concentration for three case study regions, China, Sub-Saharan Africa and Venezuela, for use in biological effects models. By combining the general climate change calculated with several GCMs with the observed patterns of interannual climate variability, reasonable scenarios of temperature and precipitation variations can be created. Generalizations of this procedure to other regions of the world are discussed.

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* This is the first in the series of PAN-EARTH articles on the environmental impacts of global climate change (Harwell, 1993).

Climatic Change **23:** 293–335, 1993.

1. Introduction

Many scientific studies warn of a rapid global climate change during the next century as a result of increased greenhouse gases in the atmosphere (National Research Council (NRC), 1979, 1983, 1987; World Meteorological Organization, 1986a, 1986b; the 'State-of-the-Art' reports of the Department of Energy (MacCracken and Luther, 1985a, b; NRC, 1985; Trabalka, 1985; Strain and Cure, 1985; White, 1985); Ramanathan, 1988; Houghton *et al.*, 1990). These all suggest that the effects of greenhouse warming will become dominant over the natural variability of climate, including the effects of volcanic eruptions, El Niño/Southern Oscillations (ENSOs), internal atmospheric and oceanic circulation variations, and possible solar variations, and all agree that surface air temperatures will rise, precipitation patterns will change, and sea level will rise.

Even though such projections of the future are relatively crude, it is important to begin the assessment of the human impacts of potential climate changes on a global basis, as has been recently done for the United States (Smith and Tirpak, 1989). Because of time lags inherent in the climate system, current actions will commit society to future climatic change and hence, the impacts on humans and the biosphere. The results of current impact analyses, even if imperfect, will be useful in the design of future climate models. This will guide the modelers to produce not only parameters of interest to atmospheric scientists, but also parameters that will be needed by society to develop policies to minimize climate change and to develop technological responses to ameliorate the human impacts on climate change and the impacts of climate change on humans and the biosphere. The techniques used for scenario generation by Smith and Tirpak (1989), however, have serious deficiencies that significantly limit the value of their impacts assessments. In this paper, an improved technique is presented and demonstrated in three case studies.

General circulation models (GCMs) of the climate simulate the entire globe with fairly coarse resolution (typical grid spacing of 500 × 500 km). However, biological and societal impacts are felt on local and regional scales. The coarse GCM resolution not only limits the ability of the models to produce accurate simulations on a global scale, but it also makes it difficult to derive parameters on scales smaller than that of the models. In order to study regional impacts, scenarios which can be applied to many different activities and systems are essential.

Table I lists the steps that are necessary to determine the impacts of climate change on humans and the biosphere. Clearly, it is beyond our current capabilities to complete this process, especially steps 8–10, although Glantz (1989a, b) is beginning work on new ideas for step 9. In this paper, specific choices from steps 1–3 are used with a new technique for step 5 to further progress in this endeavor.

The potential causes of climate change of concern for the next 100 yr are discussed first. Then, the requirements for a useful scenario are presented. The specific areas of impact, with the needed parameters and the required spatial and temporal resolution, are described next. Various possible techniques for creating

TABLE I: Steps necessary to determine the impact of climate change on humans

1. Select type of climate change, e.g. greenhouse warming.
2. Select system that affects humans, e.g. agriculture, water resources, ecosystems.
3. Select technique for determining impact, e.g. ecological and crop simulation models.
4. Determine the necessary climatic parameters for use in impact analysis, based on 1, 2, and 3.
5. Choose technique to generate climate scenarios.
6. Generate scenarios.
7. Determine range of impacts using technique selected in 3 and scenarios from 6. Conduct sensitivity analyses using technique selected in 3 to estimate uncertainties and error propagation and to identify most sensitive components.
8. Repeat 1–7 for all possible combinations of 1, 2, 3, and 5.
9. Determine all human technological, sociological, economic, political, and military responses to each impact from above, singly and in all combinations.
10. Assign probabilities to each choice and result above, and determine the net human impact.

regional scenarios are discussed, with emphasis on using the output from climate models. A new technique, combining climate model output with synoptic climatology, is presented. Finally, this technique is applied to case studies in China, Sub-Saharan Africa, and Venezuela.

2. Potential Causes of Future Climate Change

Both the past and future courses of climate change are determined by a combination of external forcings, unforced internal fluctuations, and the response characteristics of the climate system. These causes can be divided into natural and anthropogenic causes. We must consider both of these potential causes of climate change in order to understand the future climate and its impacts on humans and the biosphere. For this paper, however, scenarios will be created based only on anthropogenic causes, since these will probably become dominant in the next century and GCM-based calculations for natural causes are not available. The possibility of large deviations from these scenarios, due to unforeseen natural causes, will also be studied at the same time by using arbitrary scenarios.

A. Natural Causes of Climate Change

Solar Variations

The sun provides the energy source for all weather on the earth, and the global balance between incoming sunlight and outgoing longwave radiation determines the climate. Small variations (~ 1–2%) in solar radiation have the potential for causing climate changes as large as those projected for increases of greenhouse gases. Precise observations of the sun have only been taken for the past decade (Willson and Hudson, 1988). They show, however, that solar variations during this period have been so small that they would not be important compared to the other forcings discussed in this section (Foukal and Lean, 1990). Because these high-quality observations have only been taken for a short period of time (approximately the past 10 yr), one cannot rule out past or future variations of the sun that would be larger. But on the time scale of centuries, solar variations do not now seem to be an important factor. A new observation (Friis-Christensen and Lassen, 1991) speculates that length of the solar cycle may be an indicator of the solar constant and that these longer term variations may also be solar-related, but this remains to be established. Early GCM studies of large solar constant changes gave results very similar to CO_2 changes. Thus, GCM CO_2-based calculations may be interpreted as combinations of solar constant and CO_2 changes. Unfortunately, there may be important differences between these two forcings; moreover, solar-constant GCM studies are not available for regional impact analysis.

Volcanoes

Large volcanoes can significantly increase the concentration of stratospheric aerosols, decreasing the amount of sunlight reaching the surface, and reducing surface temperatures by several tenths of degrees for several years (Hansen *et al.*, 1978, 1988; Robock, 1978, 1979, 1981, 1984a). Because of the thermal inertia of the climate system, volcanoes can even be responsible for climate changes over decades. A significant part of the observed global climate change of the past 100 yr can be attributed to the effects of volcanic eruptions (Pollack *et al.*, 1976; Robock 1979). Since large eruptions occur fairly frequently, this component of climate change will have to be considered when searching past climate for a greenhouse signal and when projecting future climate changes. Very few GCM studies of volcanic eruptions have been conducted, and none are available for regional impact studies.

Tropospheric Aerosols

Natural sources, such as forest fires and sea spray, generate atmospheric aerosols in the troposphere. The concentrations vary greatly in space and time, and local sources are important. Furthermore, these aerosols can produce either warming or cooling, depending on their concentration, color, size and vertical distribution. It is not now possible definitively to determine their role in global climate. Aerosols may also have indirect effects on climate, by changing cloud optical properties (Charlson *et al.*, 1987). There have been no GCM studies to date that include natural tropospheric aerosol variations and provide detailed regional output, so this forcing is not used here to create scenarios.

Internal Variations

Even with no changes in the external forcings discussed above, climate still exhibits variations due to internal redistributions of energy both within the atmosphere and between the atmosphere, ocean, and cryosphere. The total amplitude and time scales of these variations are not well known, and therefore pose an additional difficulty in interpreting the past record and projecting future climate change. Some studies suggest that these random variations can have amplitudes and time scales comparable to climate changes expected to be caused in the coming decades by greenhouse warming (Lorenz, 1968, 1991; Hasselmann, 1976; Robock, 1978; Hansen *et al.*, 1988). A large El Niño/Southern Oscillation (ENSO) event, such as that in 1982–83, can draw large amounts of energy out of the oceans and warm the surface climate for a few years; this warming is then superimposed on any warming caused by the greenhouse effect. As our understanding of ENSO variations improves, it becomes possible to account for this factor in interpreting past global climate change (Angell, 1988). All the GCM simulations naturally include some internal climate system oscillations in their output. However, because of the limitations of these models (as discussed below), especially their inability to simulate ENSO events, the GCM results to date must be used with the understanding that they may do a poor job of estimating the internal variability of the climate system (Mearns, 1989a).

B. Anthropogenic Causes of Climate Change

Anthropogenic Greenhouse Gases

The concentration of a number of radiatively-important trace gases in the atmosphere is increasing because of human activities. Because they are very effective absorbers of longwave radiation, only small (trace) amounts can have large effects on the radiation balance. These gases include carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide (N_2O), and stratospheric water vapor (H_2O). According to Houghton *et al.* (1990), the relative contributions of these anthropogenic gases to radiative forcing in the past decade were CO_2 – 56%, CFCs – 24%, CH_4 – 11%, N_2O – 6%, and stratospheric H_2O – 4%. Over the next century, the increased radiative effects of these gases are expected to dominate global climate change, producing a warmer, wetter world. Many modeling groups have used GCMs to study the effects of gradual or instantaneous increases of greenhouse gases, and these form the basis for construction of scenarios for impact analysis.

In generating scenarios, an important component is the timing of future climate changes. This depends not only on the timing of the changes in the forcing (i.e., how rapidly trace gas concentrations increase), but also on the thermal inertia and the sensitivity of the climate system to these forcings. A simpler question to ask is, 'What would be the change in global average surface air temperature if the CO_2 concentration in the atmosphere were doubled from the pre-industrial level, all other climate forcings were held constant, and the climate became completely adjusted to the new radiative forcing?' This is called the 'equilibrium climate sensitivity' to a CO_2 doubling. When discussing climate change, it is sometimes convenient to refer to an 'equivalent doubling of CO_2,' which means the effect of all the greenhouse gases together that would have the same effect as doubling CO_2. This would obviously occur with less than a doubling of CO_2 itself, because the changes in the concentrations of the other anthropogenic greenhouse gases currently contribute approximately the same amount of radiative forcing as does CO_2. While it is reasonable to lump all the greenhouse gases together for the purposes of calculating the radiative effect, the other individual effects of these gases, such as fertilization of plants by CO_2 or chemical reactions of CFCs leading to ozone depletion, must be determined based on the actual concentration of each gas. The $2 \times CO_2$ calculations used in this paper are for the purpose of evaluating the climatic effects of an equivalent doubling of CO_2.

Deforestation

The Earth's radiative balance can also be changed by variations of surface properties. While interactions with the oceans, which cover 70% of the Earth's surface, are considered internal to the climate system, land surfaces can exert a strong influence on the climate. Human activities such as deforestation, not only provide a source of CO_2 and CH_4 to the atmosphere, but also change the surface albedo and rate of evaporation of moisture into the atmosphere. Detailed land surface models, incorporating the effects of plants, are now being developed and incorporated into climate model studies (Dickinson, 1984; Sellers *et al.*, 1986). The results of Shukla *et al.* (1990), who modeled the deforestation of the Amazon region, provide important information for use in construction of scenarios for South America.

Nuclear winter

By far the greatest potential anthropogenic environmental disaster would be caused by a nuclear holocaust, as suggested by Crutzen and Birks (1982). The resulting cold and dark conditions at the earth's surface have been labeled 'nuclear winter' (Turco *et al.*, 1983), and have been the subject of numerous studies, including energy-balance climate model (e.g, Robock, 1984b; Vogelmann *et al.*, 1988) and GCM calculations (e.g., Covey *et al.*, 1985; Malone *et al.*, 1986; Ghan *et al.*, 1988) and studies of naturally-occurring analogs, such as forest fires (e.g,, Robock, 1988a, b, 1991b; Veltishchev *et al.*, 1988). Pittock *et al.* (1986), Harwell and Hutchinson (1985), and Turco *et al.* (1990) have presented detailed summaries of the latest findings, which have confirmed the earlier work and solidified the bases of this theory. Steve Ghan, at the Lawrence Livermore National Laboratory, has produced GCM simulations of nuclear winter and provided calculations that will be used in generating scenarios for the specific case study regions in this paper.

Tropospheric Aerosols

Normal human activities put aerosols into the atmosphere. This includes industrial and agricultural emissions, as well as particles from biomass burning. Because the average residence time of these aerosols in the troposphere is only about one week, due to washout and rainout processes, their distribution is quite variable. Because their effects on climate, and potential to cool and offset greenhouse warming, has not been well studied (Charlson *et al.*, 1991), there is no basis at the present time for including tropospheric aerosols in detailed scenarios. In the future, however, they may be found to have important regional implications, such as the suggestion by Pat Michaels (personal communication) that the lack of warming in the continental United States over the past century at the same time as the globe warmed (Hanson *et al.*, 1989) may have been related to the increased aerosol loading over the United States. There have been no GCM studies to date including tropospheric aerosols as an anthropogenic forcing that provide detailed regional output, so this forcing will not be used at this time to create scenarios.

3. Creation of Scenarios

A. Requirements for a Good Set of Scenarios

In order for scenarios to be useful in studying the impacts of anthropogenic climate change, they must have certain properties. We would like to know precisely, for every potential human system that will be affected and for every type of impact analysis, the specific distribution of the relevant climate parameters on the appropriate spatial and temporal scales. Since even the best means that we now have to do this, GCMs, do not do this well on a regional basis, we must consider certain principles to guide us in the use of GCM output to create scenarios (Table II):

TABLE II: Requirements for a good set of scenarios

1. Must reflect the physics of the current climate system.
2. Must include all of the important anthropogenic forcings, individually and in combination.
3. Must include a broad range of climate changes, in order to account for possible natural forcings and to test effects of model sensitivities.
4. Must specify the temporal variations of parameters at each location.
5. Must not be treated as forecasts, but only as sensitivity tests.

1. Must Reflect the Physics of the Current Climate System

If the scenario is inconsistent with the currently observed behavior of the climate system, it will be difficult to interpret the relevance of the predicted impacts. An obvious attempt to satisfy this requirement is to use the results of the best available GCMs in the creation of the scenarios. However, as shown below, GCMs do not yet accurately reproduce the current climate on a regional basis. Until GCMs are sufficiently improved, their output must be modified, based on our understanding of the current observations, in order to use them in scenarios. If some models provide better simulations than others, however, they are the ones that should be used modified for scenario creation. For example, in the tropics, the weather variable with the largest interannual variation is precipitation, not temperature. In Venezuela, there is no seasonal cycle of temperature; only a seasonal change in the diurnal temperature range between the dry and wet seasons. When it is drier, and hence less cloudy, the daily maximum temperature is higher and the daily minimum temperature is lower, but the mean stays approximately the same. On the other hand, precipitation varies by large amounts from month to month and year to year. If the GCM does not provide a proper representation of these physical processes, then its output cannot be used without modification.

2. *Must Include All of the Important Anthropogenic Forcings, Individually and in Combination*

Increases in anthropogenic greenhouses gases are not the only potential human-induced change in climate, as discussed above. In order to understand the total anthropogenic influence, deforestation and nuclear winter should also be considered. Because deforestation and increased greenhouse gases are linked, they should also be considered together. However, since nuclear winter is unlikely (we hope) compared to greenhouse warming and deforestation, useful scenarios need not include it.

3. *Must Include a Broad Range of Climate Changes, in Order to Account for Possible Natural Forcings and to Test Effects of Model Sensitivities*

A set of arbitrary changes of the relevant climate parameters should be used, for several reasons. One is to test, singly and in combination, the sensitivity of the biological impacts models to changes in these parameters. Second, if causes of climate change other than the ones we are studying, such as a change in the frequency of ENSO events or volcanic eruptions were to occur, we could gain information about the potential impacts of these changes. Third, these results will also determine which parameters are the most important in influencing human impacts. And fourth, this information will provide important feedbacks to climate modelers to improve their models and their model diagnosis to provide the important and effects-relevant parameters. GCM modelers traditionally look at 500-mb vorticity patterns in the mid-latitudes to verify the accuracy of their models. Only recently have they begun to look at other parameters such as tropical rainfall patterns in their model diagnoses. Input from scenario analyses will help to guide their work.

4. *Must Specify the Temporal Variations of Parameters at Each Location*

If, for example, it is estimated that monthly-average precipitation will increase by 20% at a particular location, but given that the crop model needs daily precipitation amounts, how should this additional precipitation be distributed throughout the month as compared to the present? Should the current precipitation be increased by 20% each day, should additional rainy days be added, or should the rainy season be extended? The impact on crops might depend on this difference. In a monsoon region, if precipitation increases, should the date of the beginning of the monsoon be earlier, or should the dates remain the same and the rain be more intense? If the latter, should the timing of rain events change or be the same? If temperature increases, should the daily temperature increase by the same amount as the daily minimum? Should all days in the month have the temperature changed by the same amount, or should some days' temperatures increase more than others? All questions of this type must be specified explicitly in each scenario, because the impact on crops can significantly differ with different ways of imposing changes in weather variables.

5. *Must Not Be Treated as Forecasts, but Only as Sensitivity Tests*

Because the best scenarios that we can create are subject to so many limitations, at this point it is very important to avoid the temptation to assign probabilities to the results. In other words, even the best scenario created with the best GCM applied to the best crop model cannot be considered as a forecast of the impact of humans on climate and used for policy decisions. With the possible exception of sea-level rise, it will be impossible for the foreseeable future to identify winners and losers of future climate change. We may be able to identify human systems that are potentially more vulnerable than others to certain scenarios, but the unknowns about regional climate change and human responses preclude at this time the use of the words *winners, losers*, and *forecast.*

B. *Defining the Required Information for Regional Impacts*

In order to produce a scenario of future climate for use in effects assessment, it is first necessary to know the particular activity that will be studied and the techniques used for assessment, and the dependence of the activity and techniques on different climate parameters. Only then can useful scenarios be provided that include information on the important parameters with the appropriate temporal and spatial resolution.

Scenarios will be needed to study the effects on a large number of systems that affect humans, including agriculture, forests, transportation, water resources, wetlands, human health, rivers, lakes, estuaries, biodiversity, coastal resources, air pollution, recreation, electricity demand, wind, solar and hydro electricity generation, and societal and political systems. For each of these, the most important climate parameters may be different. For instance, ocean currents, frequency and strength of oceanic storms, winds, frequency of fog, sea-ice distribution and thickness, and sea level as it affects navigation in shallow straits and harbors, will all be important for ocean transportation. For agriculture, temperature, precipitation, cloudiness, wind, CO_2 concentration, intensity of ultraviolet light, frequency of severe storms, and soil moisture, will all be important, although of different relative importance for different crops in different areas of the world at different times of the year. In addition, the frequency of rare, but extreme, events, such as hurricanes, drought, flooding, tornadoes, hailstorms, heat waves, and frost, may be more important than shifts in the mean of climate parameters. And for each of the important paramters, the appropriate spatial and temporal distribution of the parameter must be provided. For example, the ocean currents may only be needed on a monthly basis in 1000×1000 km boxes, while the diurnal cycle of temperature might be needed at a specific location on a hillside near a coastline where a rice crop is being grown.

It should be pointed out that in the above discussion another factor, technological change, has not been considered. The predominant factor in changes in virtually all the activities listed above during the past century has been technological developments, not climate. It is not known how to predict future technological change and its interaction with climate. Furthermore, technological or political reaction to perceived climatic change, such as developing drought-resistant crops, or implementing large-scale reforestation, may completely dominate future impacts. Societal reactions, such as mass migrations or revolutions, may also be more important than the direct effects of changing climate parameters on specific activities.

There are several possible methods to assess the effects of climate change, including simulation models, statistical models, studies of distributions of vegetation in current and past climates, field and laboratory experiments, and historical records of responses to weather and climate extremes. For each of these techniques, different types and resolutions of climatic information may be necessary in the scenarios.

In this paper we focus on two techniques for impact analysis, ecosystem distributions as a function of mean temperature and pressure (for China), and the IBSNAT crop models, which need daily maximum temperature, minimum temperature, precipitation, and insolation (for Sub-Saharan Africa and Venezuela). These are discussed in detail in Section 4.

C. *Techniques for Creating Climate Change Scenarios*

Given that we can accomplish the steps discussed above (steps 1–4, Table I), and that we have a list of climate parameters that need to be specified in scenarios of the future, how can appropriate and defensible scenarios be produced? The different possibilities are discussed here.

Data from the Instrumental Record

Smith (1989) used the warm decade of 1930–1939 as an analog for a warmer future world. This method has two problems. First, it is now as warm as that decade in many parts of the world, and scenarios of a climate quite different from the present one are needed. Second, the 1930's probably were warm because of a lack of volcanic aerosols for the preceding two decades, and it is now warm probably due to the compensating effects of cooling by volcanic aerosols and warming by more greenhouse gases and the largest El Niño of the century (Robock, 1991a). Superimposed on both of these time periods is the natural variability of climate, which has been different in the different periods. Hence, using a different period with the same mean climate, but produced by different causes, may produce an entirely different distribution of climate parameters and not be a good analog. Jäger and

Kellogg (1983) similarly point out that scenarios created by considering the warmest and coldest years of a particular time period do not produce useful regional information.

Paleoclimatic Information

The same problem as discussed above also applies to using paleoclimatic information. It has been suggested by Budyko (1991), among others, that three warm epochs in the past, the Holocene Optimum of 5000 years ago, the last Interglacial Optimum of 125 000 years ago, and the Pliocene Optimum of 3–4 000 000 yr ago, could be used as analogs for future warm periods. However, as shown by MacCracken and Kutzbach (1991), warm periods in the past were caused by different forcings than potential greenhouse-gas-induced warming and had different seasonal and latitudinal distributions of solar energy. Therefore, they may be quite inappropriate to use for scenarios of the next century. One might expect quite different distributions of atmospheric circulation, precipitation, monsoons, and seasonal cycles produced by greenhouse gases as compared to Milankovitch forcing.

Synthetically-Generated Time Series

Mearns (1989b) suggested that if the statistical structure of time series of the relevant meteorological parameters were known, then artificial time series with the correct statistical properties could be generated. This approach has the advantage that the variability can easily be changed to test the effect of hypothesized future changes in this property. However, this method is not now practical for two reasons. One is that we would like to have physically consistent variations of all parameters, and a physical, not just statistical, model is necessary to combine variations of, say, temperature, precipitation, and insolation. The other reason is that the statistical structure of many important variables is not well known or easily expressed, such as for tropical rainfall or insolation.

Scenarios From Climate Models

GCMs of the Earth's atmosphere have been used by five different groups [Oregon State University (OSU; Schlesinger and Zhao, 1989), National Center for Atmospheric Research (NCAR; Washington and Meehl, 1984), Goddard Institute for Space Studies (GISS; Hansen *et al.*, 1984), Geophysical Fluid Dynamics Laboratory (GFDL; Wetherald and Manabe, 1986), and the United Kingdom Meteorological Office (UKMO; Wilson and Mitchell, 1987)] to calculate how the 'equilibrium' global climate will change in response to doubling the CO_2 concentration in the Earth's atmosphere. The UKMO, OSU, GFDL, and GISS results are currently available at NCAR for analysis and use in generation of scenarios. Groups in the U.S.S.R., Australia, West Germany, and Canada are also doing equilibrium calculations. In addition, the GISS, GFDL, and NCAR models have been coupled to ocean models of varying complexity and used to calculate the time-dependent transient response of the climate system to gradual increase of greenhouse gases.

The GISS transient calculations, made with a simplified, non-dynamic ocean model, are also currently available at NCAR. The GFDL and NCAR transient calculations were made with full oceanic GCMs, and therefore allow more possible modes of response.

Although these calculations have a coarse resolution and disagree on regional distributions of climate change, they have been used for creating ranges of scenarios for studying the impact of climate change (Smith, 1989). In order to create scenarios for individual locations, at least five related approaches have been recently suggested. Ackerman and Cropper (1988) described an overall framework for combining GCM output, local climatology, and expert judgment to create scenarios (Figure 1). This framework guides the scenario creation in the present paper. In their procedure, if a GCM does an adequate job of simulating the current climate, or if the GCM does not do a good job but the bias is understood, the GCM information is used directly to create scenarios. Four recent papers provide techniques to accomplish this. They all assume that the regional-scale GCM output has some useful information, and suggest ways to go from the large GCM scale down to the local scale. Wigley *et al.* (1990) evaluated multiple linear regression techniques for calculating sub-grid-scale information. Turco (1988) suggested a method for using the seasonal cycle to scale the local changes from GCM output. Karl *et al.* (1990) developed a statistical technique employing empirical orthogonal functions to obtain local information. Smith (1989) has actually used simple procedures, such as adding the $2 \times CO_2 - 1 \times CO_2$ GCM results and transient GCM differences to observed data, to create scenarios for United States impact studies. However, none of these techniques provides guidance on creating scenarios if the GCMs do such a poor job that the $2 \times CO_2 - 1 \times CO_2$ results cannot be trusted, since the model errors resulting in the poor $1 \times CO_2$ simulations are still inherent in the $2 \times CO_2$ results. In the methodology and case studies presented below, this problem is addressed.

GCMs have large deficiencies in their ability to predict the future. In the first place, it cannot be assumed that the climate will gradually warm, as is implicit in interpolating between a $1 \times CO_2$ and a $2 \times CO_2$ equilibrium simulation. Nor can it be assumed that a smooth transient simulation with only greenhouse gases for forcing and a simple mixed layer ocean is applicable. Even though the global climate has warmed during the past century (Jones, 1988; Hansen and Lebedeff, 1988; Vinnikov *et al.*, 1990), this warming may be entirely due to natural variations in the climate system and totally unrelated to greenhouse gases (Robock, 1978; Lorenz, 1991). Future climate change attributable to internal variation in the climate system is difficult to establish (Lorenz, 1991). Volcanic eruptions may play an important climate role, depending on the frequency and amplitude of future eruptions (Robock, 1991a). Although Hansen *et al.* (1988) included volcanic eruptions in some of their transient scenarios, the future level of volcanic activity cannot be predicted. Cooling cannot be excluded from climate change scenarios for the next few decades and must be considered in any set of scenarios.

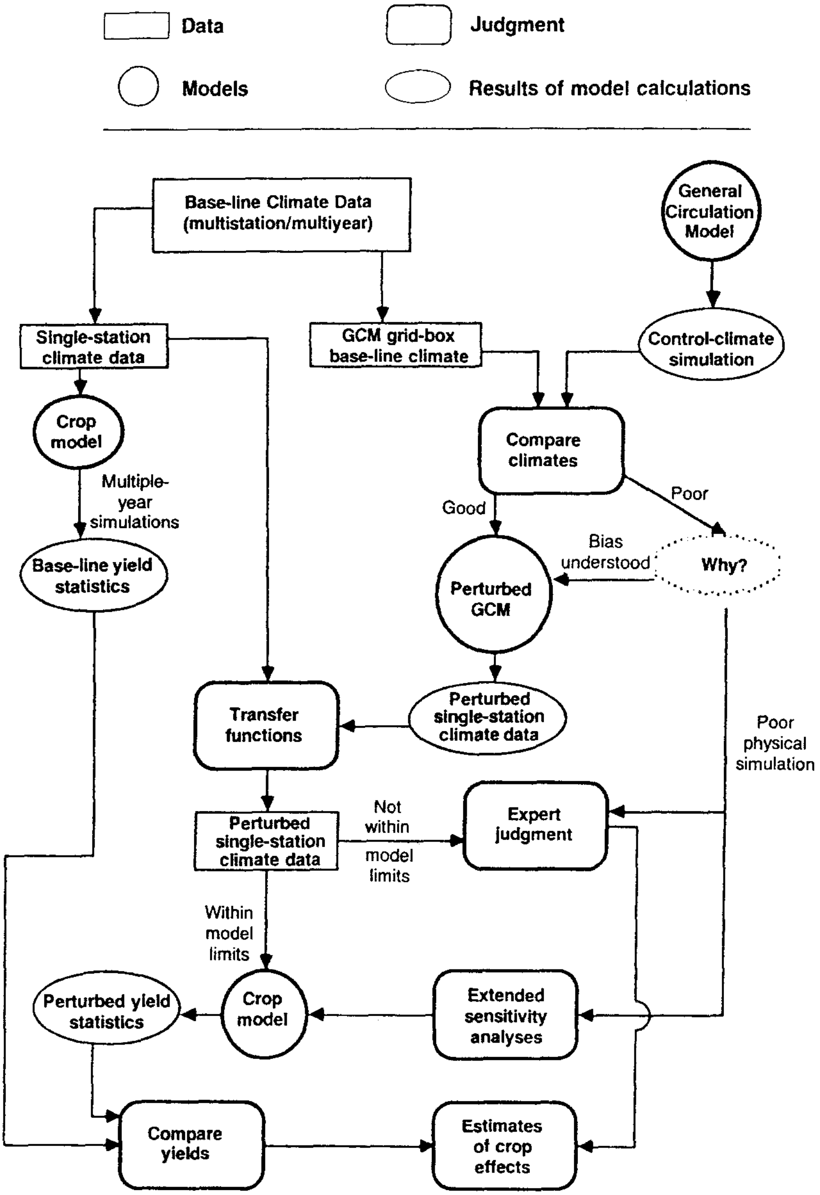


Fig. 1. Process for scaling climate projections to crop models, from Ackerman and Cropper (1988).

In the second place, GCMs do not properly treat many important physical and biological processes. Clouds, soil hydrology, and ocean circulation, and the biological impact on the first two of these and on CO_2 levels, are the major deficiencies that we can identify today. For example, when the UKMO included more detailed, but not necessarily more accurate, cloud microphysics, in their $2 \times CO_2$ experiments, the global sensitivity decreased from a 5.2 °C warming to 1.9 °C warming

(Mitchell *et al.*, 1989). When Stouffer *et al.* (1989) coupled an oceanic GCM to their atmospheric GCM in a transient experiment, they actually found a period of cooling in the Southern Hemisphere (SH) as the Northern Hemisphere warmed. Even after a 200-yr integration during which the atmospheric CO_2 concentration increased by a factor of 4, the air temperatures in the high latitudes of the SH failed to warm. When the system is warming everywhere, different parts of the climate system warm at different rates. Therefore, gradients will be established that lead to anomalous responses unresolvable in equilibrium calculations. No greenhouse warming calculations have yet included a biosphere model, yet recent calculations of Amazon deforestation (Shukla *et al.*, 1990) with the National Meteorological Center GCM coupled with the SiB biosphere model (Sellers *et al.*, 1986) showed large effects of the biosphere on soil moisture and cloudiness. The sensitivity was found even with a very crude, GCM-grid-size biosphere model. How can GCM output be used to evaluate the effects of climate change on agriculture or forests, when the simulation does not include this biology in its calculations?

GCMs are not highly accurate in reproducing the current climate for the United States (Grotch, 1988) and other parts of the world (Grotch and MacCracken, 1991; Kalkstein, 1991; and see Case Studies, Section 4), because of the above problems and the resolution of the models. If GCMs do not include the physics necessary to satisfactorily simulate the current climate, it is difficult to accept simulations of altered climate.

Using GCMs to drive nested-grid models, with higher resolution (1 × 1°) over the region of interest, lead to more realistic simulations of regional climate in that region (Giorgi, 1990; Giorgi and Mearns, 1991), but it is prohibitively expensive to run high-resolution models on a global basis. Because the boundary conditions of a nested grid depend on the inaccurate simulations of a lower-resolution global GCM, this technique does not offer promise for the creation of regional scenarios, because the high-resolution information in the region of interest will be contaminated with erroneous boundary conditions.

The variability of climate may also change as the mean changes. Rind (1991), in a number of simulations, showed that, as the climate warms the temperature variability decreases while the hydrological variability increases. Can a GCM be used to predict reliably this aspect of climate scenarios? Variability of the current climate is already very large, especially that of the hydrological cycle. It is the extreme events, such as the 1988 midwestern US drought, hurricanes Gilbert in 1988 and Hugo in 1989, or the Sahel drought of the recent past, that can have devastating effects on humans. Will the future climate actually be more variable than at present?

Another aspect of climate variability is the scale of temporal and spatial variation. If there is a question about the models producing the correct variability for the current climate, how can such variability be ascertained in the future? Particularly difficult are the problems of determining sub-grid-scale variation and distinguishing future climates from the present large background variability on local scales.

Arbitrary Scenarios

Guided by the results of the GCMs and the needs for the study of a particular impact, a climatologist could arbitrarly specify combinations of parameters that would be self-consistent within the range of uncertainty in our knowledge and would span the range of possible future climates. This could be the same for many different impacts, in order for all to study the same scenario, or could be tailored to a specific impact, so that the sensitivities could be optimally determined. This is a necessary part of any set of scenarios, as discussed above.

D. *Previous Studies*

The largest impact analysis study done to date was the EPA study of the impact of climate change on the United States (Smith and Tirpak, 1989). Smith (1989) presented five requirements for their scenarios that are similar to those proposed here, but then decided to use a very different methodology for creating scenarios, basing them either solely on $2 \times CO_2$ equilibrium GCM results or the analog climate of the 1930's. They used several different GCMs to determine $2 \times CO_2 - 1 \times CO_2$ parameters from the nearest GCM grid point and added this difference to time series from observations. This procedure, which is now also being used for global impact analysis studies under EPA sponsorship (ICF, 1989), makes it very difficult to interpret the results. (This particular international study will also use arbitrary scenarios, if the resources are available, but without any specification of the temporal variability.)

The EPA procedure violates the first three requirements for scenario development (Table II) and does not provide a method to deal properly with temporal variability, the fourth requirement. A crucial difference between the EPA procedure and ours is that they act as if GCMs can produce useful regional distributions of future climate change and leave out the vital step of comparing GCM simulations of the current climate with observations. The EPA approach assumes that the GCM physics is sufficiently accurate to provide regional information about the future. Unfortunately, the error in scenarios produced by the EPA approach may be so large that the biological effects they predict are determined by their error rather than by climate change. In the procedure offered here, the physics of the actual climate system, as derived from observed climatic variability, is implicitly accounted for.

The EPA procedure has been used in several previous impact studies, such as the Parry *et al.* (1988) and Adams *et al.* (1990) studies of agricultural impact, and the Croley and Hartmann (1989) study of Great Lakes levels. All these studies suffer from the same problems discussed above.

As an example of the EPA technique, Tables III-V present the results of using the programs supplied by EPA to current investigators working on the international impact assessment. The program requests a latitude and longitude and then supplies output from the nearest GCM grid point from the UKMO, GISS, and

TABLE III: GCM simulations for grid point nearest to 115° E, 30° N, in China

Month	Temperature (°C)			Precipitation (mm/day)			Solar (W/m^2)		
	1×CO$_2$	2×CO$_2$	Diff	1×CO$_2$	2×CO$_2$	Ratio	1×CO$_2$	2×CO$_2$	Ratio
Values at	115.0	30.0	from UKMO at	116.3	32.5	16 25			
1	−11.6	−4.3	7.29	0.6	0.5	0.90	144.	152.	1.05
2	−5.7	1.7	7.35	1.3	1.0	0.78	166.	183.	1.10
3	2.8	10.4	7.59	3.6	4.3	1.21	168.	179.	1.07
4	10.2	16.8	6.65	5.9	6.5	1.11	164.	176.	1.07
5	16.5	22.7	6.14	7.9	7.5	0.94	184.	217.	1.18
6	22.2	27.0	4.89	6.2	7.8	1.26	220.	234.	1.06
7	25.7	29.6	3.98	6.3	6.9	1.10	245.	254.	1.04
8	25.1	29.2	4.08	4.9	6.0	1.22	252.	247.	0.98
9	20.3	25.2	4.87	2.4	2.8	1.16	202.	220.	1.09
10	12.1	19.0	6.86	1.9	2.1	1.07	146.	159.	1.08
11	−1.9	7.7	9.60	1.0	1.4	1.32	139.	128.	0.92
12	−9.9	−1.6	8.32	0.5	0.7	1.28	133.	131.	0.98
Values at	115.0	30.0	from GISS at	120.0	27.4	31 16			
1	7.0	9.8	2.74	1.1	1.2	1.13	136.	133.	0.98
2	9.6	12.2	2.59	2.3	1.5	0.68	143.	153.	1.07
3	13.8	17.1	3.31	3.0	3.0	1.03	174.	180.	1.04
4	18.2	22.0	3.15	3.2	4.2	1.33	230.	229.	1.00
5	22.7	26.3	3.58	5.3	4.8	0.91	252.	263.	1.04
6	24.7	29.4	4.69	6.4	9.6	1.51	264.	278.	1.05
7	26.7	31.3	4.52	8.4	11.0	1.30	255.	263.	1.03
8	27.2	31.4	4.18	9.1	11.2	1.23	243.	258.	1.06
9	23.3	26.8	3.52	6.1	8.0	1.30	215.	228.	1.06
10	19.1	22.0	2.92	4.3	4.2	0.98	179.	178.	0.99
11	12.5	16.2	3.72	2.4	2.7	1.15	137.	138.	1.00
12	8.7	11.1	2.42	1.2	1.1	0.94	115.	125.	1.09
Values at	115.00	30.0	from GFDL at	112.5	28.9	16 27			
1	−18.5	−11.5	7.02	2.0	2.4	1.22	51.	71.	1.40
2	−9.5	−4.0	5.48	4.0	6.0	1.48	49.	77.	1.57
3	0.7	7.4	6.72	8.4	9.3	1.10	93.	103.	1.11
4	10.7	17.2	6.49	5.3	6.9	1.29	140.	146.	1.04
5	19.7	24.0	4.30	5.5	5.5	1.00	145.	155.	1.07
6	25.1	28.1	3.00	1.6	2.8	1.81	193.	183.	0.95
7	29.0	31.4	2.38	2.4	3.7	1.55	186.	181.	0.97
8	29.5	30.9	1.46	2.9	2.7	0.94	179.	172.	0.96
9	26.8	28.4	1.56	1.1	2.4	2.16	174.	166.	0.96
10	15.4	18.3	2.85	3.0	2.8	0.95	130.	128.	0.99
11	−5.5	0.4	5.89	3.7	4.0	1.09	78.	93.	1.19
12	−17.4	−11.5	5.90	1.6	1.6	0.98	44.	86.	1.97

GFDL models for the current climate and a 2×CO$_2$ climate. Table III presents results for 115° E, 30° N, in the middle of the agricultural region in China. Tables IV and V are for similar regions in Niger (5° E, 15° N) and Venezuela (65° W, 5° N). The procedure calls for the investigators to insert the temperature differ-

TABLE IV: GCM simulations for grid point nearest to 5° E, 15° N, in Niger

Month	Temperature (°C)			Precipitation (mm/day)			Solar (W/m^2)		
	$1\times CO_2$	$2\times CO_2$	Diff	$1\times CO_2$	$2\times CO_2$	Ratio	$1\times CO_2$	$2\times CO_2$	Ratio
Values at 5.0 15.0 from UKMO at 3.8 17.5 1 22									
1	18.6	23.8	5.11	0.2	0.0	0.22	249.	257.	1.03
2	22.5	28.6	6.08	0.3	0.1	0.45	279.	286.	1.03
3	26.9	33.7	6.82	0.6	0.6	1.00	303.	301.	0.99
4	29.2	36.1	6.90	0.8	1.0	1.22	322.	308.	0.96
5	30.5	37.2	6.73	1.6	2.0	1.22	321.	323.	1.01
6	30.1	36.5	6.42	2.1	2.5	1.19	327.	325.	1.00
7	30.6	38.3	7.72	2.2	1.5	0.65	330.	336.	1.02
8	31.6	37.4	5.78	2.0	2.4	1.23	326.	323.	0.99
9	28.0	32.1	4.07	3.0	5.1	1.67	298.	294.	0.99
10	25.3	29.8	4.43	0.5	1.0	1.84	284.	284.	1.00
11	21.8	28.1	6.27	0.3	0.1	0.36	243.	261.	1.08
12	19.1	24.7	5.65	0.1	0.1	0.44	240.	247.	1.03
Values at 5.0 15.0 from GISS at 10.0 11.7 20 14									
1	23.7	28.0	4.34	0.9	0.7	0.75	249.	243.	0.98
2	25.2	30.3	5.02	0.7	1.5	2.24	273.	266.	0.98
3	26.8	31.5	4.77	1.2	2.3	2.01	293.	285.	0.97
4	27.7	32.5	4.72	2.1	2.8	1.35	303.	296.	0.98
5	28.3	31.7	3.40	2.9	4.0	1.35	291.	290.	1.00
6	27.8	31.0	3.18	2.9	4.1	1.44	286.	285.	1.00
7	26.0	30.4	4.34	5.7	6.3	1.10	277.	279.	1.01
8	25.2	28.4	3.22	6.8	8.6	1.28	264.	266.	1.01
9	24.1	27.3	3.26	6.5	6.7	1.03	246.	259.	1.05
10	23.3	27.3	3.92	3.3	3.1	0.92	255.	255.	1.00
11	23.7	28.5	4.76	1.5	1.3	0.84	246.	248.	1.01
12	23.0	28.7	5.67	1.0	0.9	0.85	242.	239.	0.99
Values at 5.0 15.0 from GFDL at 7.5 15.6 2 24									
1	16.5	20.8	4.34	0.5	0.3	0.56	110.	110.	1.00
2	20.0	23.5	3.50	0.4	0.4	0.99	119.	121.	1.02
3	24.2	27.1	2.93	0.4	0.5	1.15	134.	134.	1.00
4	27.1	31.4	4.22	0.9	0.9	1.01	134.	134.	1.00
5	27.3	31.6	4.34	1.6	1.2	0.75	134.	134.	1.00
6	27.3	30.1	2.80	1.8	3.1	1.69	129.	125.	0.97
7	26.1	27.7	1.68	2.7	3.3	1.22	124.	124.	1.00
8	26.6	29.4	2.74	1.8	2.4	1.31	126.	120.	0.96
9	26.4	30.4	4.00	1.8	1.2	0.68	125.	128.	1.02
10	25.2	28.7	3.53	0.4	0.8	1.99	124.	121.	0.98
11	20.5	26.2	5.73	0.3	0.3	1.03	112.	110.	0.98
12	18.6	20.9	2.31	0.2	0.4	1.85	107.	104.	0.98

ences and precipitation and insolation ratios directly into the daily weather inputs that drive the crop models.

The problems in using this method are clear from even a quick perusal of the tables. The differences between the models for the simulations of the current

TABLE V: GCM simulations for grid point nearest to 65° W, 5° N, in Venezuela

Month	Temperature (°C)			Precipitation (mm/day)			Solar (W/m^2)		
	$1\times CO_2$	$2\times CO_2$	Diff	$1\times CO_2$	$2\times CO_2$	Ratio	$1\times CO_2$	$2\times CO_2$	Ratio
Values at	−65	5.0	from UKMO at	−63.8	7.5 40	20			
1	20.9	27.3	6.41	2.1	1.4	0.66	210.	239.	1.14
2	22.3	29.8	7.55	1.7	1.5	0.88	230.	266.	1.16
3	25.1	32.0	6.92	1.5	2.1	1.42	251.	289.	1.15
4	26.6	31.6	4.99	3.0	4.0	1.36	266.	287.	1.08
5	24.9	28.4	3.51	7.6	8.7	1.16	245.	246.	1.00
6	23.9	27.7	3.80	8.5	10.1	1.19	244.	244.	1.00
7	24.0	27.3	3.30	10.2	11.0	1.08	242.	249.	1.03
8	23.6	27.1	3.52	7.4	6.3	0.85	256.	272.	1.06
9	23.4	27.2	3.85	5.1	4.3	0.85	266.	271.	1.02
10	24.1	28.3	4.23	7.1	7.7	1.09	248.	253.	1.02
11	23.5	27.4	3.97	6.8	6.6	0.97	224.	238.	1.06
12	21.6	25.7	4.07	3.5	3.3	0.93	219.	225.	1.03
Values at	−65.0	5.0	from GISS at	−60.0	3.9 13	13			
1	24.8	28.5	3.73	6.4	5.1	0.80	253.	253.	1.00
2	24.8	28.9	4.08	6.1	3.8	0.62	258.	268.	1.04
3	25.1	29.7	4.63	5.8	4.5	0.79	268.	284.	1.06
4	25.7	30.2	4.53	4.6	4.6	1.00	273.	283.	1.04
5	26.6	30.5	3.93	3.6	3.7	1.02	266.	274.	1.03
6	27.8	31.3	3.50	1.6	2.1	1.34	265.	268.	1.01
7	28.0	31.7	3.70	2.0	2.3	1.14	268.	268.	1.00
8	27.6	31.9	4.31	2.9	2.7	0.95	281.	277.	0.99
9	27.1	31.4	4.39	5.2	4.8	0.94	289.	288.	1.00
10	26.2	30.5	4.32	7.2	5.9	0.81	279.	278.	1.00
11	25.3	29.8	4.47	6.8	5.3	0.79	260.	263.	1.01
12	24.7	28.9	4.16	5.5	6.0	1.10	250.	251.	1.01
Values at	−65.0	5.0	from GFDL at	−67.5	6.7 40	22			
1	20.2	22.4	2.18	3.2	3.4	1.06	155.	153.	0.99
2	20.2	23.9	3.71	2.8	3.0	1.06	161.	166.	1.03
3	20.6	24.0	3.34	3.8	4.4	1.15	167.	172.	1.03
4	21.6	24.2	2.61	3.5	3.7	1.06	184.	171.	0.93
5	21.3	23.1	1.78	6.4	6.6	1.04	152.	132.	0.87
6	20.7	23.2	2.48	4.4	5.9	1.34	137.	130.	0.95
7	20.8	23.2	2.39	5.1	5.7	1.11	139.	130.	0.93
8	20.7	24.2	3.48	4.3	3.8	0.89	132.	158.	1.20
9	21.5	24.6	3.16	6.2	7.2	1.16	138.	144.	1.04
10	21.7	24.3	2.57	7.4	7.3	0.99	133.	132.	0.99
11	20.5	23.1	2.57	3.1	6.4	2.04	137.	124.	0.91
12	19.5	22.1	2.56	2.4	4.3	1.81	138.	133.	0.97

$1\times CO_2$ climate are much larger than the differences between the $1\times CO_2$ and $2\times CO_2$ climates in each model. For example, the January temperature for China (Table III) has a range of 25.5 °C for the $1\times CO_2$ simulations, for Niger 7.2 °C (Table IV), and for Venezuela 4.6 °C (Table V), while the projected $2\times CO_2 - 1\times CO_2$ temperature changes are much smaller. The GFDL $2\times CO_2$

prediction for January for China is −11.5 °C, 18.5 °C *colder* than the GISS 1 × CO_2 temperature. Moreover, even larger differences are found for precipitation and insolation. There are also large differences between mode predictions of the amplitude and seasonal cycles of the temperature differences. For example, for China GFDL and UKMO predict larger temperature changes in winter than summer, while GISS predicts the opposite. The precipitation and insolation ratios show large month-to-month variability, with no correspondence from model to model. Clearly, the results of an impact analysis that used these data should be critically examined. Which model, if any, is to be given more weight? Does the model-to-model variation give any reasonable idea of the expected variation in impacts?

One obvious problem with the EPA procedure is that the relevant model grid points for a specific impact location come from different locations, because of the coarseness of the model grids. One would think that the procedure could be improved if maps were made of model output and the scenarios were based on values interpolated to the exact impact location. However, as will be seen later in the case studies, even this does not measurably improve the model simulations of the current climate, and does not render the direct GCM model output useful for scenario creation.

Some general patterns are clear from these tables, however. All the models give warming, for all months of the year for all locations, as is to be expected from simple greenhouse theory. During the rainy season, for all the cases, there is generally an increase in precipitation. The insolation changes (related to cloudiness changes) show no patterns. This general information can be used in scenario creation.

E. Methodology

In order to begin the development of a reasonable method to produce scenarios for impact assessment, it is necessary to look at specific cases. Because there are so many possible combinations of systems that will be affected, techniques for effects assessment, techniques for generation of scenarios, and varying locations on the planet, this paper addresses specific combinations of these variables in order to illustrate the problems in scenario generation and provide some solutions.

The systems studied were agriculture and specific biome distributions. Agriculture is the most important system that affects humans, and techniques have been developed to study the impacts. For agriculture, the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) crop simulation models (IBSNAT, 1988; Hoogenboom, 1989) have been adopted. For biomes, a statistical model was used that relates temperature and precipitation to ecological system parameters (Hammond, 1972; Chang and Gauch, 1986; Chang, 1988). The IBSNAT agricultural models require daily values of maximum temperature, minimum temperature, precipitation, and insolation. The biome models are cruder, requiring only monthly average temperature and precipitation.

For the reasons discussed above, scenarios based on both GCM output and arbitrary specifications were created. The method of Ackerman and Cropper (1988) (Figure 1) was used for these case studies, because they provide the most logical and detailed procedure for dealing with GCM output. However, they do not provide a method for producing scenarios in cases where the GCMs do a poor job of simulating the current climate, which is true for every case study.

In this paper a new procedure (Figure 2) is developed for combining GCM output with climatic information in order to produce scenarios, even when the GCMs give poor regional simulations. This is a substitute for the 'Expert Judgment' box of Figure 1. If the GCM does a poor job of simulating the current regional climate, there is still general information contained in the calculations that can be useful in creating a scenario. All GCMs show that when CO_2 is doubled, the global average climate will warm and the global average precipitation will increase (Mitchell,

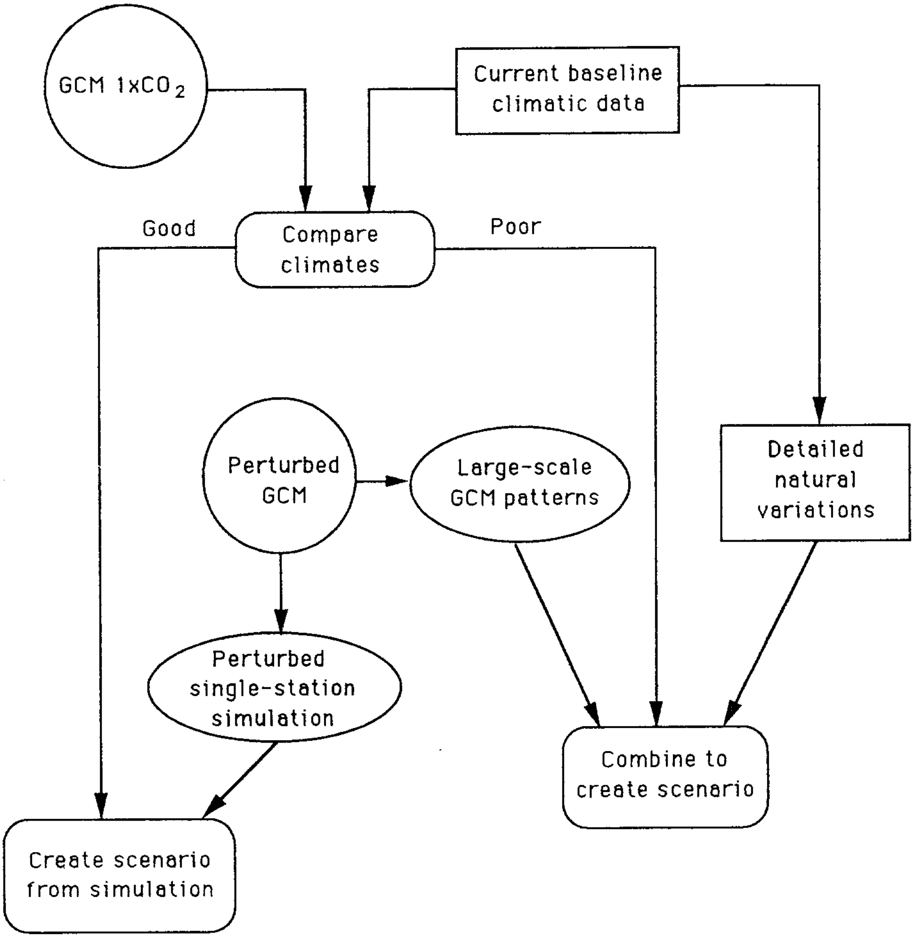


Fig. 2. Improved procedure for scenario creation.

1991). Data analyses (Vinnikov *et al.*, 1990; Vinnikov and Yeserkepova, 1991) also show this but show larger increases in precipitation than the models for the same temperature change. Therefore, even though we cannot be sure of the regional details, there is no reason to expect any particular region not to behave in this general way, although decreasing rainfall cannot be excluded in some regions. Thus, we can combine the arbitrary specification of climate change based on this general behavior of climate models and data with specific knowledge about the modes of natural interannual variation of specific regions to create regional climates.

Every region has interannual climate variations. In the midlatitudes, such as in China, there are large variations of both temperature and precipitation. In the tropics, such as Sub-Saharan Africa and Venezuela, the dominant year-to-year variations are of precipitation. In the new procedure, this information is used to create scenarios for a warmer, wetter world, with the precipitation increasing in the same way that it does now between wet and dry years.

The assumption in using a scenario based only on GCM output and calculating the $2 \times CO_2 - 1 \times CO_2$ difference, as has been done previously, is that the same physics governs the climate system in a warmer world as in the present, and the physics used is that represented by the GCM. In the procedure here, the same assumption is made, but the physics is specified by the climate system, not by the computer model. Because the computer model is in error, as seen by comparing its output to current data, we do not want to retain the erroneous physics. However, if it is assumed that the climate system will continue to vary in the future in the same way that it does today, then by using current interannual differences, the possible scenarios do not conflict with the known physics. Although current interannual precipitation variations are not necessarily linked to temperature variations, we use large-scale temperature-precipitation relations to specify the amount of precipitation changes, but use observations to specify the character of the changes.

Of course, in a world with a drastically altered climate, there may be non-linear responses that cannot be captured by this procedure, and can only be studied by appropriately detailed, validated models, of which none presently exist. But for greenhouse warming, the current interannual variations are as large as the predicted variations in the tropical regions. Thus, we have reasonable confidence that the behavior of the future climate will follow the same rules as does the current climate. Even if a GCM does a good job of simulating the current climate, this does not mean that it can be trusted to give a good regional scenario for the future climate, and so the new scenario generation technique should also be employed in this case in addition to the GCM-based method.

4. Case Studies

The case studies used to explore the scenario development methodology are associated with the PAN-EARTH Project, a series of national- and regional-level case studies on the effects of climate change on the ecological and agricultural systems of China, Japan, Venezuela, and several countries in Sub-Saharan Africa. The PAN-EARTH Project derived from the International Council of Scientific Unions' Scientific Committee on Problems of the Environment (SCOPE) project on the global consequences of nuclear war (ENUWAR) (Pittock *et al.*, 1986; Harwell and Hutchinson, 1985). The present PAN-EARTH case studies focus on greenhouse, nuclear winter, and other anthropogenic climate change. Through a number of focused workshops, the participants in the PAN-EARTH Project (including all the authors of the present paper plus many additional scientists from around the world) have worked to develop generic and regional scenarios of climate change, identify the ecological and agricultural systems of importance in each region, develop biological effects assessment tools, including adapting ecosystem and crop simulation models to the specific conditions of selected sites in each case study region, and conduct sensitivity analyses on those models to identify the vulnerabilities of the regions to climate change and identify specific research needed to reduce errors of effects assessment predictions. This paper presents one component (scenarios development for regional assessments); other components of these case studies will be reported in subsequent articles.

Each of the case studies in this section is conducted in the same way, following the procedures outlined in Figures 1 and 2. First, the type of human system and types of climate change to be studied are specified. From this the needed variables and resolutions are derived. Then, the GCM output from $1 \times CO_2$ calculations from the available models are compared to the observations. If the models are not accurate at simulating the current climate, which turns out to be the case for all the studies here, then a scenario is specified based on the procedure in Figure 2. Deforestation GCM results do not exist for China, and nuclear winter scenarios have already been created (Harwell, 1988). Therefore, only greenhouse warming scenarios were created for China. Nuclear winter scenarios were created for both Africa and Venezuela, and deforestation scenarios were created for Venezuala.

A. *China*

The climate scenarios for China were created for use by H. S. Chang to study the distribution of terrestrial ecosystems in China in a greenhouse-warmed world. One method is to relate the current natural vegetation distribution to monthly-average temperature and precipitation distributions, and then use new distributions of climate data to calculate new ecosystem distributions (Hammond, 1972; Chang and Gauch, 1986; Chang, 1988). This requires changes in monthly-average temperature and precipitation, which can be applied to each station. Uchijima *et al.* (1992) has recently used this technique to study vegetation distributions in Japan, and found a high correlation between the vegetation pattern and integrated temperatures. For Japanese vegetation, precipitation was almost always sufficient and temperature was the controlling factor.

The next step in the production of scenarios is to assess the GCM climatologies.

Climatological data (30-yr averages) from 683 stations in China (Figure 3a) were compared to simulations of the current climate from 4 GCMs: OSU, GISS, GFDL, and UKMO. None of these models did a good job of simulating the regional

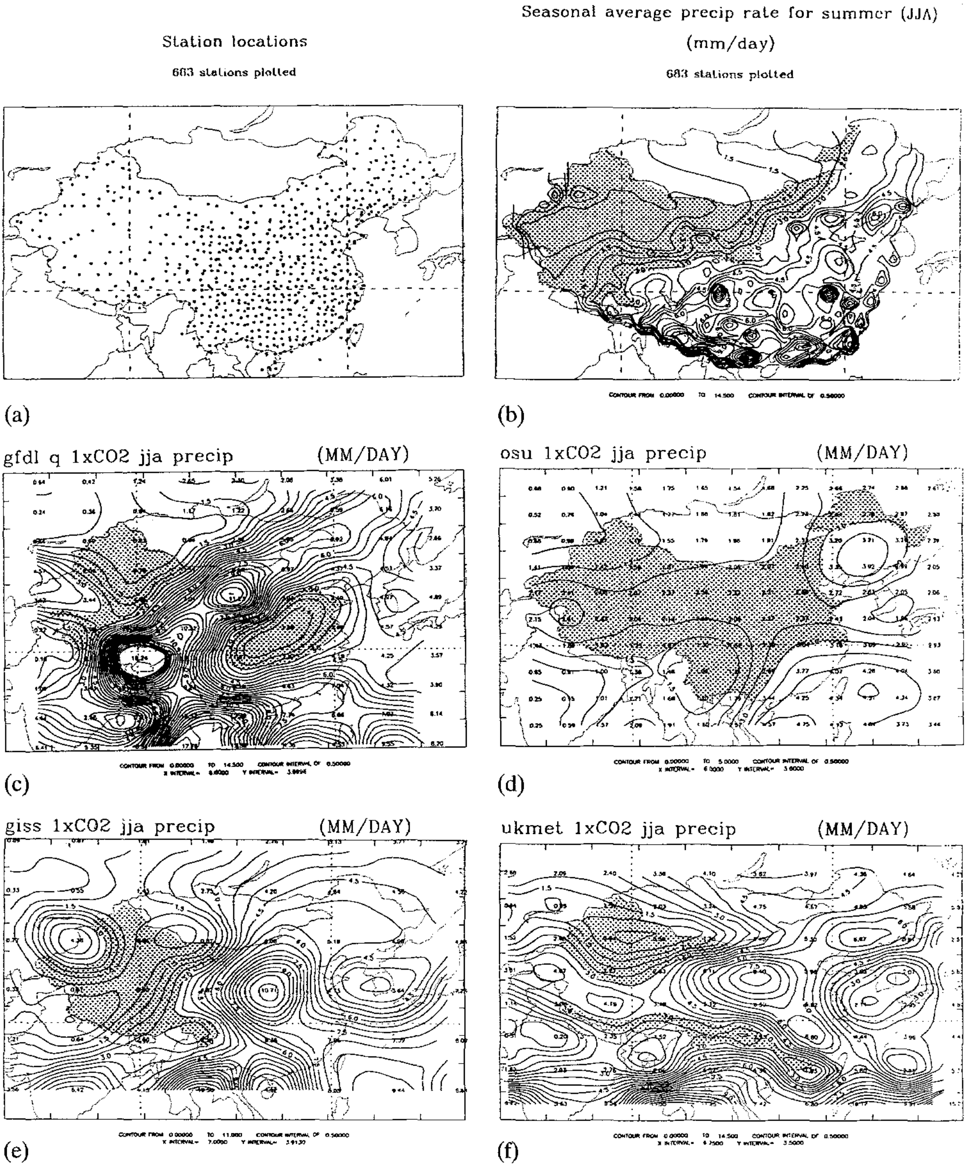


Fig. 3 (a). Location of 683 stations in China used for data plots in Figures 3b. and 4a. (b) Observed summer (June, July, August) average precipitation rate for China. Rates below 3 mm day^{-1} are shaded. The contour interval is 0.5 mm day^{-1}. Ignore contours outside of China, which are artifacts of the contouring program. (c) Simulation of summer precipitation rates for China by the GFDL GCM. Rates below 3 mm day^{-1} are shaded. The contour interval is 0.5 mm day^{-1}. (d) As in (c) for the OSU GCM. (e) As in (c) for the GISS GCM. (f) as in (c) for the UKMO (indicated here as UKMET) GCM.

climate of China for either temperature or precipitation for any of the seasons, in agreement with the results of Grotch (1988) for the United States. Figures 3 and 4 give examples of these comparisons for summer precipitation and winter temperature, where it is easily seen that the patterns have large errors.

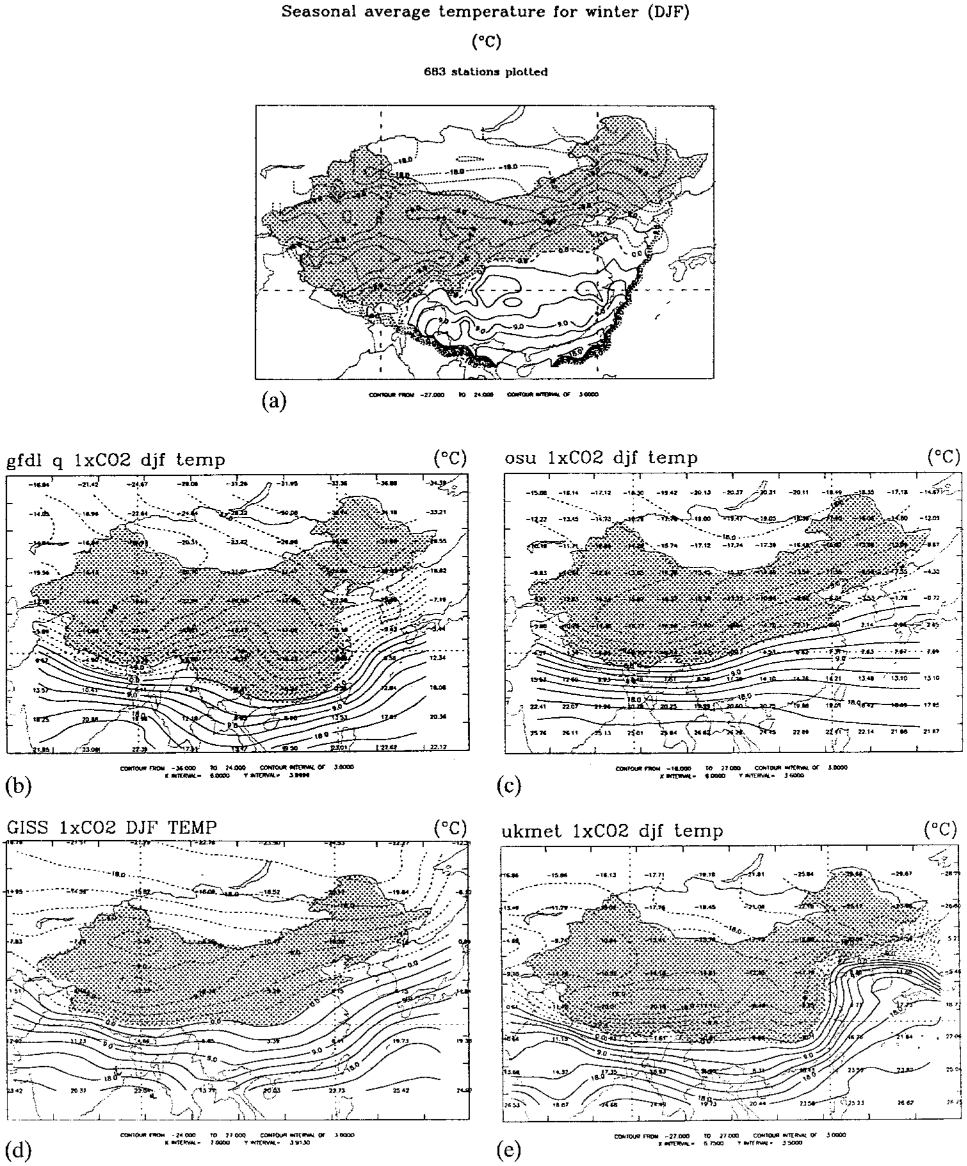


Fig. 4 (a). Observed winter (December, January, February) average temperatures for China. Temperatures below 0 °C are shaded. Station locations are shown in Figure 3a. The contour interval is 3 °C. As in Figure 3, ignore contours outside of China. (b) Simulation of winter temperature for China by the GFDL GCM. Temperatures below 0 °C are shaded. The contour interval is 3 °C. (c) As in (b) for the OSU GCM. (d) As in (b) for the GISS GCM. (e) As in (b) for the UKMO (indicated here as UKMET) GCM.

Since the detailed patterns of the $2 \times CO_2$ GCM simulations cannot be used to make regional predictions, a scenario, shown in Table VI, was created using the general GCM patterns, which show warming and more precipitation in a warmer world. Based on all the GCM and data studies done for the midlatitudes, a warming of 2–4 °C, and an increase of precipitation of about 20% seems the most likely result of an equivalent doubling of CO_2. The GCMs do not provide guidance as to the regional or seasonal distributions of these changes within China. Figure 5 shows, for example, simulations for the four models of the ratio of precipitation in a $2 \times CO_2$ world to that in a $1 \times CO_2$ for the summer. The patterns indicate no coherence, and since the $1 \times CO_2$ simulations are also poor (Figure 3), they offer no guidance to the regional distribution of precipitation change. Therefore, the scenarios (in Table VI) should be applied to all the stations in China for all seasons. The range of combinations of temperature and precipitation changes is given to investigate the sensitivity of the biome distributions, and to provide for extreme but less probable (given our current understanding) changes. Since only monthly-average values are needed for this biome distribution model, no further specification of the temporal variations of temperature and precipitation are needed. This is not

TABLE VI: Greenhouse warming ($2 \times CO_2$) scenarios for China

These scenarios should be applied to all the stations in China for all seasons.

Temperature	Precipitation
−2 °C[a]	−20% no change +20%
No change[a]	−20% no change +20% +40%
+2 °C[b]	−20% no change +20%[b] +40%
+4 °C[b]	−20% no change +20%[b] +40%
+6 °C[a]	−20% no change +20% +40%

[a] Extreme scenarios for testing model sensitivity.

[b] Most likely scenarios for $2 \times CO_2$.

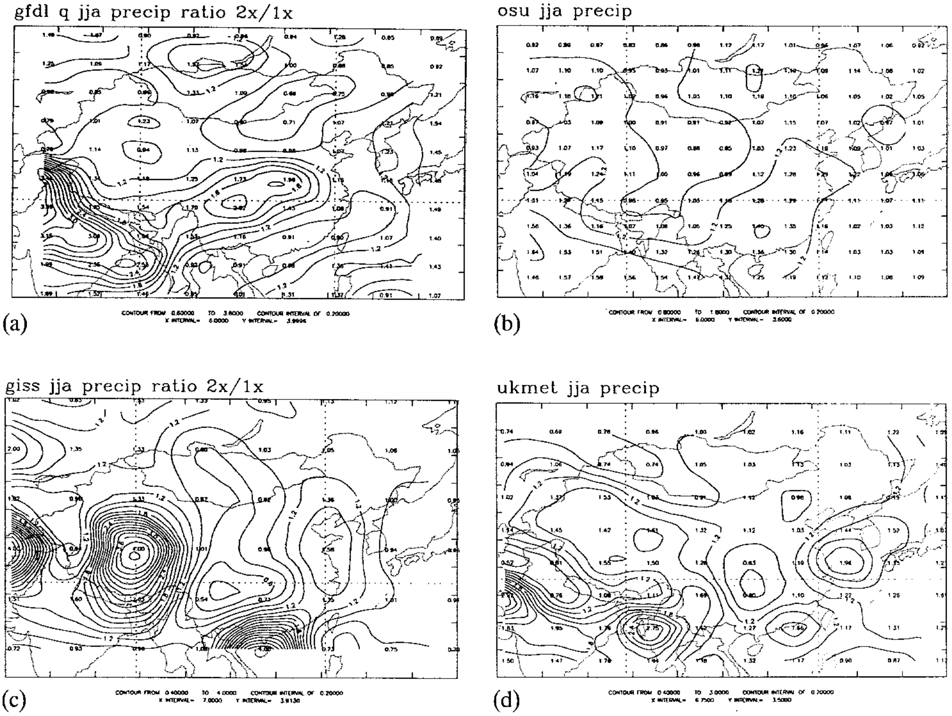


Fig. 5 (a). Simulation of changes in summer (June, July, August) precipitation rates (ratio of 2 × CO_2 to 1 × CO_2) for China by the GFDL GCM. The contour interval is 0.2. (b) As in (a) for the OSU GCM. (c) As in (a) for the GISS GCM. (d) As in (a) for the UKMO (indicated here as UKMET) GCM.

the case for the crop and ecological assessments conducted for Africa or Venezuela.

Because these scenarios are to be applied equally at all stations, a random spatial variation, with zero mean, could also be applied, although the GCM results are not good enough to describe what this pattern should be. The standard deviation of the temperature and precipitation variations should be approximately half the value of the changes in Table VI, to account for the presently observed scale of variations.

B. Sub-Saharan Africa

Scenarios were created for Sub-Saharan Africa to use with the IBSNAT crop simulation models (IBSNAT, 1988; Hoogenboom, 1989), which are being used generally by the PAN-EARTH project (Harwell, 1989) to evaluate the impact of climate change on several crops. The IBSNAT models require inputs of daily values for maximum temperature, minimum temperature, precipitation, and insolation. For greenhouse warming and nuclear winter, the available GCM results are first described. Then, the evidence from data is presented and the scenarios created. The results in this section are derived from work begun at the PAN-EARTH Sub-

Saharan Africa Workshop (Harwell, 1989). Desertification is also a concern in this region, but there are no GCM results available to produce scenarios.

$2 \times CO_2$

The calculations from three GCMs – OSU, GISS, and GFDL – were available for use in these scenarios. None of the models accurately simulated the current climate (Harwell, 1989). As an example, Figure 6 shows the precipitation patterns for July from observations (data provided by Graham Farmer from the archives of the Climatic Research Unit, University of East Anglia) and from the three GCMs. It is clear that all the models underestimated the precipitation in the heavy rain belt at 10° N and overestimated the rainfall in the desert to the north. The rainfall patterns of all the models are as different from each other as they are from reality.

For the $2 \times CO_2$ calculations, all the models showed warming, but again, there was no consistent pattern or amplitude. Figure 7 gives the July simulations for $2 \times CO_2 - 1 \times CO_2$ for the three models. Grid-point temperature changes range from less than 1 °C to more than 5 °C. The GISS GCM, the only one with a diurnal cycle, shows that the amplitude of the diurnal cycle decreases with warming. This is caused by enhanced downward infrared radiation from additional CO_2 and water vapor in the air, which is more effective at night when not competing with sunlight. During the rainy season, enhanced cloudiness would produce a similar effect, causing warming at night and cooling during the day, superimposed on a general warming trend. Precipitation changes (not shown) for the same simulations range from large increases to large decreases, with no coherent patterns, and with the average overall increase of about 25%.

Nuclear Winter

Detailed output from only one GCM was available for analysis, from the Lawrence Livermore National Laboratory version of the OSU model (Ghan *et al.*, 1988). The recent summary of expected nuclear winter climatic effects by Turco *et al.* (1990) and comments accompanying Ghan's graphical results provided additional guidance in scenario generation. Because more detailed information was available for the Venezuela case study region, and there was no reason to suspect that the African perturbations at similar latitudes would be much different, the scenarios described in detail in the Venezuelan case study were used for tropical Africa as well.

Data Considerations and the Scenarios

Temperature: The temperature scenarios for $2 \times CO_2$ are shown in Table VII. The minimum temperatures are increased more than the maximum temperatures in accordance with the model and theoretical considerations discussed above. There are also indications from data (Houghton *et al.*, 1990) that during the past 100 yr, minimum temperatures have risen more than maximum temperatures in several regions of the globe. The three prescribed levels of change correspond to different

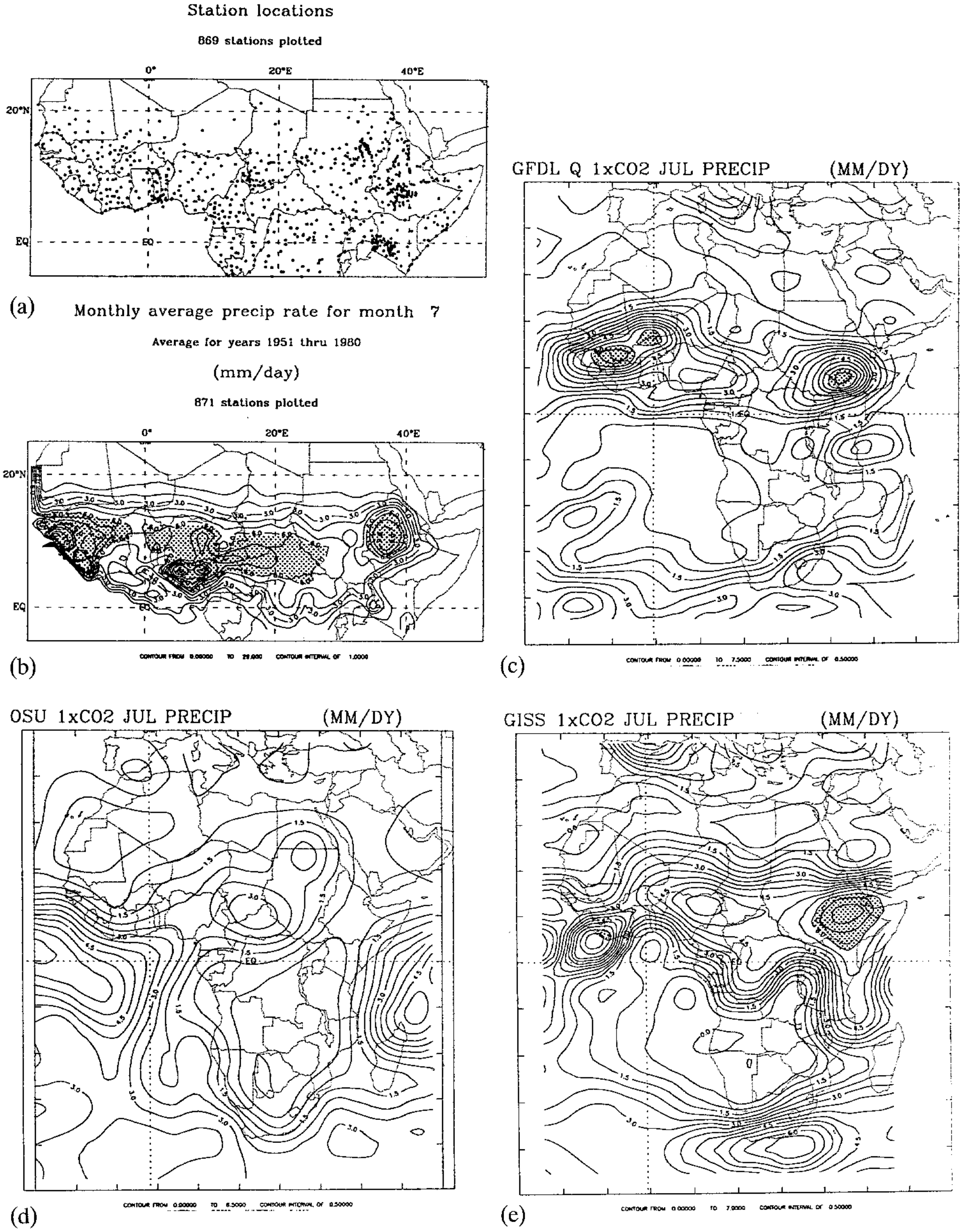
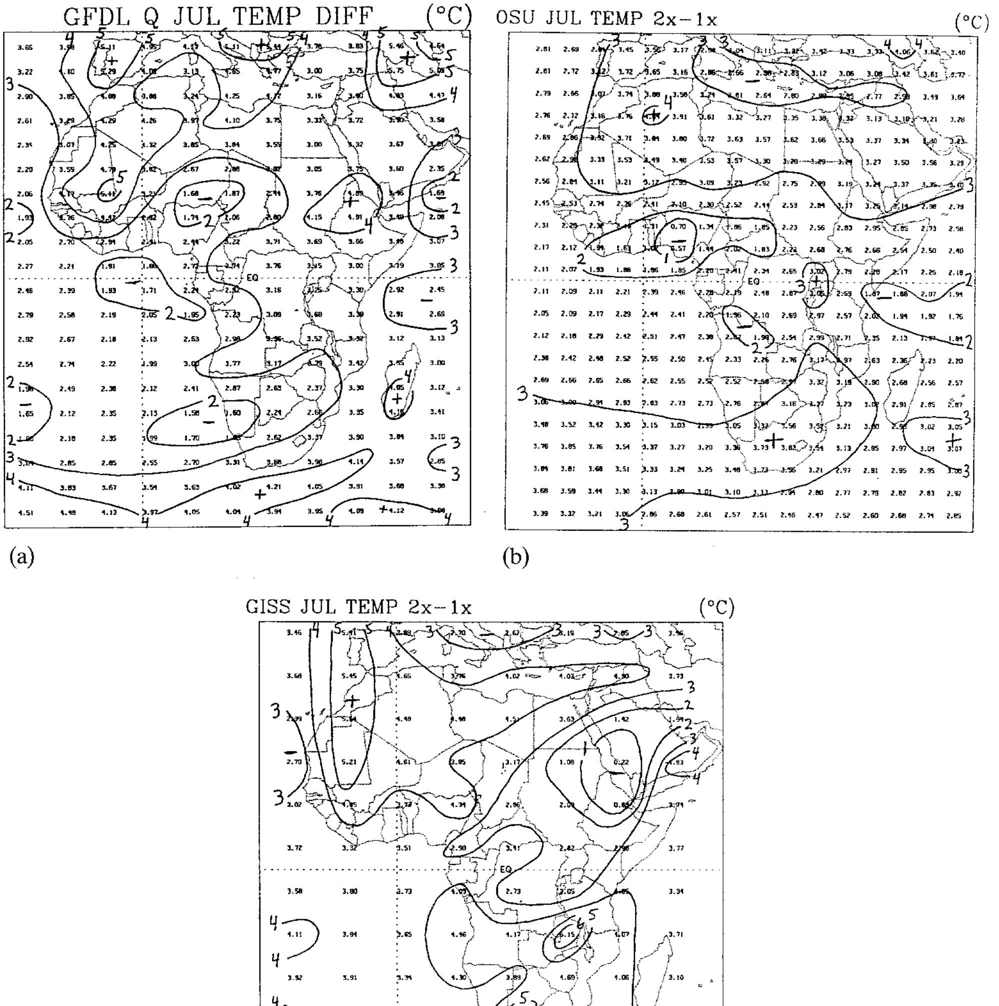


Fig 6 (a). Location of stations in sub-Saharan Africa used for data plotted in Figure 6b. (b) Observed July average precipitation rate for Sub-Saharan Africa. Rates above 6 mm day^{-1} are shaded. Ignore artificial contours in ocean. The contour interval is 1 mm day^{-1}. (c) Simulation of July precipitation rates for Africa by the GFDL GCM. Rates above 6 mm/day are shaded. The contour interval is 0.5 mm day^{-1}. (d) As in (c) for the OSU GCM. (e) As in (c) for the GISS GCM.



GFDL Q JUL TEMP DIFF (°C)

OSU JUL TEMP 2x−1x (°C)

GISS JUL TEMP 2x−1x (°C)

(a) (b) (c)

Fig. 7 (a). Simulation of July temperature increases (2 × CO_2 minus 1 × CO_2) for Africa by the GFDL GCM. The contour interval is 1 °C. (b) As in (a) for the OSU GCM. (c) As in (a) for the GISS GCM.

possible sensitivities of the climate system to greenhouse warming. The 'high' level is larger than any current models give (Mitchell, 1991), but there may be additional amplifying mechanisms (Lashof, 1989) that have not been incorporated into any of the models.

TABLE VII: Sub-Saharan scenarios for $2 \times CO_2$ and nuclear winter

$2 X CO_2$: There are 3 $2 \times CO_2$ scenarios, High, Middle and Low, corresponding to different levels of sensitivity of the climate system.

Sensitivity		Temperature	
		Max	Min
High	Dry	+5.5 °C	+6.5 °C
	Wet	+5.0 °C	+7.0 °C
Middle	Dry	+3.5 °C	+4.5 °C
	Wet	+3.0 °C	+5.0 °C
Low	Dry	+2.0 °C	+2.0 °C
	Wet	+2.0 °C	+2.0 °C

(Dry months are those with less than 50 mm of rain).

Change precipitation by +50%, +25%, 0% and −25% in combination with each of the three temperature scenarios, by changing the length of the rainy season and the intensity of the rainfall events, as described in the text.

Nuclear winter
Use the same procedure as for Venezuela (Table X).

Precipitation: In the past thirty years, the dominant climatic change in this region has been the shift from abundant rain to drought in the Sahel, with attendant severe human impacts (e.g., Lamb, 1982, 1987). The causes of these large changes in precipitation are not understood; suggested possibilities range from local human-induced desertification, to Atlantic sea-surface temperature variations, to global climatic patterns. Since GCMs are unable to model this observed change, it is not possible to rely on them for even continent-scale scenarios.

There are, however, patterns evident in the data during these dramatic climatic shifts that can be used in scenario creation. Sivakumar (1988) showed that the date of the beginning of the rainy season is much more variable than the date of the end of the rainy season in the Sahel. That is, in wet years, the rainy season begins earlier than in dry years, although it tends to end at the same time. This is true for stations that have both one and two rainy seasons per year (Figure 8a, b). This characteristic of the timing in rainfall should be incorporated into scenarios to simulate the climate system properly. In this instance, the characteristic is not evident in the GCM simulations. Sivakumar (1992) has also found, by analyzing daily rainfall in Niger, that in wet years the timing and intensity of rainstorms both change. In dry years, rainstorms are less intense and the time between rainstorms is greater. In other parts of Africa, the intensity of the rainfall events is less in dry years, but the timing is about the same (Harwell, 1989). This is related to the location and strength of the Intertropical Convergence Zone (ITCZ). This characteristic of observed climate change must also be included in the scenarios, but again it is not predicted by the GCMs.

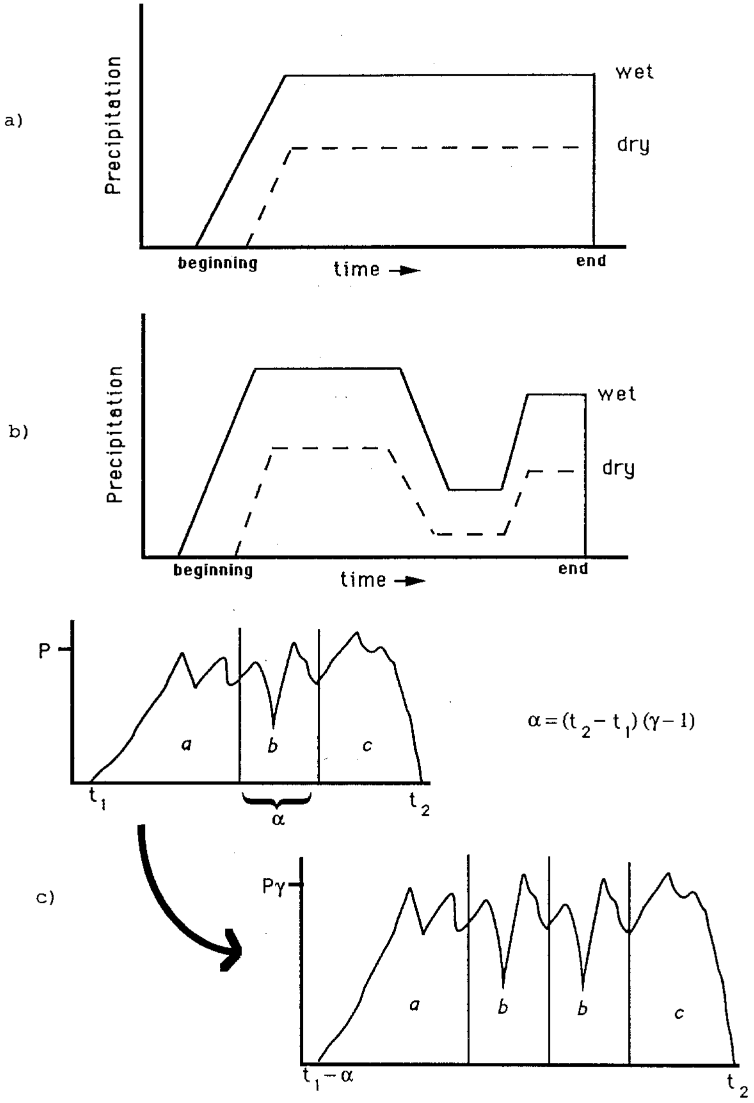


Fig. 8 (a) Schematic illustration of the envelope of rainfall amount in the Sahel for typical wet and dry years. In the wet years, the precipitation begins earlier and the intensity is larger. (b) As in (a) for a region that has a double rainfall peak. (c) Illustration of the procedure for generating a rainfall scenario for the Sahel when rainfall increases. P is the average rainfall during the rainy season for the observed time series. See text for details.

In combination with each of the three temperature scenarios, precipitation should be changed by +50%, +25%, 0% and −25% by varying the length of the rainy season and intensity of rainfall events. This can be done using the following procedure, which should be applied to daily time series of observations selected from representative dry and wet years: (a) Determine the length of the rainy season, using the criteria of Sivakumar (1988): the beginning of the rainy season is defined as the first day after 1 May when cumulative rainfall totals at least 20 mm over 3 consecutive days and when no dry spell within the next 30 days exceeds 7 days; the end of the rainy season is defined as the first day after 1 September after which no rain occurs for 20 days. (b) Increase (or decrease) the length of the rainy season by a factor, γ, specified below, by moving the beginning of the rainy season up (or back) but keeping the end date fixed. This can be done by duplicating a fraction (γ - 1) of the record in the middle of the rainy season and inserting it at that point, while moving the part before it up in time. To reduce the precipitation, the fraction (γ -1) should be removed from the middle. (a) At the same time, change the intensity of each rainfall event by the same factor, γ. (d) For each site with a double rainy season, apply this procedure separately to each rainy season, since their variations are not well correlated. This procedure is illustrated in Figure 8c. Values of γ of $1.5^{0.5}$, $1.25^{0.5}$, 1.0, and $0.75^{0.5}$ will result in total precipitation changes of +50%, +25%, 0% and −25%, as above.

C. Venezuela

A detailed paper describing the Venezuela case study (Robock *et al.*, 1992) is in preparation. A summary is presented here. As in the previous case study, scenarios were created for the IBSNAT crop simulation models for particular locations in Venezuela to specify daily values of maximum temperature, minimum temperature, precipitation, and insolation. For each type of anthropogenic forcing, the available GCM results are first described. Then, the evidence from data is presented and the scenarios created. The results in this section are partially based on the PAN-EARTH International Workshop on Climate Variability and Climate Change in Venezuela (Harwell, 1990).

$2 \times CO_2$

The OSU, GISS, GFDL, and UKMO GCM simulations of the current ($1 \times CO_2$) climate have been analyzed and compared with data from spatially-averaged precipitation values from nine $1 \times 1°$ grid cells from different rainfall regimes for precipitation and nine stations for temperature (Harwell, 1990; Robock *et al.*, 1992). In general, the UKMO model reasonably simulated current precipitation; the other models did not. Since the UKMO model simulated Venezuelan rainfall reasonably well, the scenarios are partially based on its $2 \times CO_2$ simulation, with additional general guidance from the results of the other models. Because the UKMO is the most sensitive of all the GCMs to $2 X CO_2$ (a 5.2 °C global average temperature increase), and because changes in its cloud parameterization produced a much lower sensitivity (~2 °C warming) (Mitchell *et al.*, 1989), temperature predictions from the UK model are used to fix the upper range for the scenarios.

For $2 \times CO_2$, the UKMO model shows a larger temperature increase in the dry season (January), equal to about 5 °C for all the Venezuela stations, and about 3.5 °C for the rainy season (July). This makes sense physically, since the atmosphere is clear during the dry season, and downward longwave will be more effective at heating the land. For precipitation, the UKMO model shows no change during the dry season and enhanced precipitation by about 25% during the rainy season up to July, with a reduction by 10% in August, and little change in September and October. Since this does not seem consistent with our understanding of the synoptics of the rainy season, precipitation simulations of the other three models were examined. All show enhanced precipitation during the rainy season, but not to the same extent as the UKMO model. OSU showed more of an increase (50%) in August than in July, and the other models showed less of a change, but not a reduction.

Monthly average insolation information from three of the models at grid points is available from NCAR. A review of these monthly average results (some of which are given in Table V) shows that for the Venezuela region the GFDL model predicts decreases of insolation by as much as 15% when the precipitation increases. The UKMO model also has decreases of insolation by as much as 10% for large precipitation increases, but insolation increases for smaller precipitation increases or precipitation decreases. The GISS model has virtually constant insolation, no matter what the level of precipitation. Wetherald and Manabe (1986) reviewed older versions of these GCMs which all yielded decreases in insolation when the surface warmed. Models that generate more convective clouds in response to heating can produce more precipitation and less insolation in a warmer climate. This aspect of climate models – i.e., the generation of fractional cloudiness – is one of their poorest components, as demonstrated by the wide range of results above. The experience of Venezuelan climatologists is therefore a very important source of information for the insolation portion of the scenario. As reported by Riehl in Harwell (1990), in Venezuela insolation reduces when rainfall increases, since even during non-raining times in the rainy season, cloudiness increases. This response, therefore, defines the primary scenario, and the model results will be used for secondary scenarios.

Deforestation

The GCM result of Shukla *et al.* (1990), which simulated the effects of deforestation of the Amazon, was used for the deforestation scenarios. The model includes the SiB biosphere model of Sellers *et al.* (1986) and is very high resolution, with 18 vertical levels and horizontal grid spacing of 1.8° latitude by 2.8° longitude. The current climate of South America is reproduced reasonably well (Nobre *et al.*, 1991). For Venezuela, at the edge of the deforested region, the GCM produced temperature increases of 0.5–1.5 °C and precipitation decreases of 300–600 mm yr^{-1}. The temperature increases are similar for all months of the year, and the precipitation decreases are about 20–30% for the entire year.

Nuclear Winter

The detailed output from one GCM, an updated version of the OSU model (Ghan *et al.*, 1988) kindly provided by Steve Ghan, was available to assess the impact of nuclear winter on Venezuela, and results were available for two grid points in Venezuela: 6° N, 65° W and 10° N, 65° W. The recent summary of expected nuclear winter climatic effects by Turco *et al.* (1990), and the comments accompanying the graphical results of Ghan *et al.*, provide additional guidance in generating scenarios.

The baseline Ghan prediction is similar to the OSU $1 \times CO_2$ simulation, which reproduces the Venezuelan temperatures well, but precipitation poorly. The nuclear winter changes are so large, and agree in magnitude with results from other models (not available here for analysis) that the Ghan results were used as the basis for scenario development. For precipitation, the results are quite noisy, and therefore several precipitation scenarios were produced that are based on the general expectations for this type of climate forcing, as described in the above references. The specific scenarios will not depend strongly on this particular GCM simulation.

The Ghan nuclear winter simulations used three different smoke amounts and distributions that have been standardized for GCM calculations (Pittock *et al.*, 1986; Ghan *et al.*, 1988). Three 30-day simulations were performed (all beginning on July 1) with 15, 50, and 150 Tg [$1\ \mathrm{Tg} = 10^{12}$ g] of smoke, and two 12-month simulations were run for 50 and 150 Tg of smoke. In addition a control run was made for the current climate. Other simulations, such as those by Robock (1984b) and those reported in Turco *et al.* (1990) show that for smoke injection in the Northern Hemisphere in winter, transport of smoke from midlatitudes to the tropics is reduced and the surface temperature effects are smaller. For a worst-case analysis for crop impacts, the nuclear winter scenarios presented below should be started at each month.

In the short term, only the 150 Tg case shows significant temperature changes in Venezuela, with the maximum and minimum temperature decreasing by 5–10 °C for the period 5–15 days after smoke injection. For days 20–30, the predicted temperatures are 2–3 °C above the control temperatures. In the longer term, both the 50 and 150 Tg cases show significant temperature decreases, but the maximum decreases occur in the months October-June, which is the dry season. During the rainy season, there is much more cloudiness (water clouds) and the smoke does not reduce insolation as significantly, but in the dry season the smoke alone can cause greater insolation reductions, resulting in greater temperature decreases.

Insolation is greatly reduced in the 150 Tg case for days 5–20, and somewhat reduced for the 50 Tg case. For both the 15 and 50 Tg cases, there are days with greatly enhanced insolation, perhaps caused by removal of the clouds that were present in the control simulations. For the longer term, there are early reductions of 50–70% for the 150 Tg case that last until February, then gradually return to near normal by June. For the 50 Tg case, the insolation reduction gradually increases to ~40% in November, after which it decreases to less than 10% by March.

The precipitation changes are not nearly so clear. For the 50 Tg case there are small reductions and enhancements in the rainy season, and after October, very small changes. For 150 Tg of smoke injection, July precipitation is virtually zero, after which the changes resemble the 50 Tg case.

It is interesting to note that the relative direction of changes in each parameter is different for each of the three types of climate change, because of the different physics of each forcing, as shown in Table VIII. Depending on the forcing, temperature can vary in the same or opposite direction of either precipitation or insolation, and precipitation and insolation can vary together or separately. This emphasizes the importance of Requirement 2 in Table II, that each different type of forcing must be considered separately to understand the potential impacts of human activities on climate.

TABLE VIII: Relative direction of change for different parameters for different forcings for Venezuela scenarios.

	Temperature		Precipitation	Insolation
	Max	Min		
$2 \times CO_2$	+	++	+	–
Deforestation	+	+	–	+
Nuclear winter	––	–	–	–

A double symbol (–– or ++) implies a larger change.

Data Considerations and the Scenarios

In accordance with the procedure in Figure 2, the general patterns from the GCMs described above were combined with detailed information from observations to generate climate change scenarios. The general patterns of the scenarios are summarized in Tables IX and X. The reasoning for these choices and the specific procedure for specifying the temporal patterns of the parameters are given here. The basic procedure is to take three to five years of daily data from the past climatic record, chosen so that a range of dry and wet years is represented, and modify these time series to create new scenarios.

Temperature: The temperature in Venezuela stays relatively constant throughout the year. The diurnal cycle is less during the rainy, cloudy seaon, but the daily mean does not change very much. Within a month, there are not large daily changes of temperature, as fronts rarely affect the temperature this close to the equator. Therefore, the time series of current data was modified by the same amount for each day of a month, keeping the day-to-day variance the same. This is true for all three types of scenarios.

For the $2 \times CO_2$ case, with large increases of temperature the minimum temperature is increased more than the maximum temperature, based on the physics of longwave radiation. For deforestation, temperature changes are small, and there is no good reason for distinguishing between minimum and maximum. In the case of

TABLE IX: Venezuela scenarios for 2 × CO_2 and deforestation

2 × CO_2: There are 3 2 × CO_2 scenarios, High, Middle and Low, corresponding to different levels of sensitivity of the climate system. Each is equally probable. The temperature and precipitation scenarios should be run at the same corresponding levels.

(Dry months are those with less than 50 mm of rain.)

Sensitivity		Temperature		Precipitation
		Max	Min	
High	Dry	+4.5 °C	+5.5 °C	+0%
	Wet	+2.5 °C	+4.5 °C	+40%
Middle	Dry	+3.0 °C	+4.0 °C	+0%
	Wet	+2.0 °C	+3.0 °C	+20%
Low	Dry	+2.0 °C	+2.0 °C	+0%
	Wet	+2.0 °C	+2.0 °C	+0%

Hurricanes: In a warmer world, the probability of hurricanes will increase. To simulate this, add one day in September or October with rainfall of 50 cm.

Deforestation
Change maximum and minimum temperature by +1 °C for all months. Reduce precipitation by 25% for all months. Increase insolation by 25% for all months, subject to the limitation of maximum clear sky insolation.

Deforestation and 2 × CO_2
Add 1 °C to each of the temperatures and 25% to each of the precipitation values for the 2 × CO_2 scenarios.

Note: The temporal variations within a month of temperature, insolation and precipitation are to be changed as discussed in text.

TABLE X: Venezuela scenarios for nuclear winter

Nuclear winter
For any arbitrary starting date, apply the following two scenarios:

(Dry months are those with less than 50 mm of rain.)

Smoke injection		Temperature		Precipitation	Insolation
		Max	Min		
50 TG	Dry	−5 °C	−3 °C	−25%	−25%
	Wet	−3 °C	−2 °C	−25%	−25%
150 TG	Dry	−10 °C	−5 °C	−50%	−50%
	Wet	−5 °C	−3 °C	−50%	−50%

nuclear winter, the maximum temperature is reduced more than the minimum temperature, because of the radiative physics of smoke particles, as discussed above.

Precipitation: In the current climate, rainfall is characterized by a small number of intense events, and rainier years have more events, not a longer rainy season or more intense events. Therefore, precipitation can be modified by changing the fraction of time with heavy rain rather than by scaling each event by a constant amount.

Strong hurricanes have affected Venezuela only twice during the past century, but they can have devastating consequences. GCMs do not explicity simulate hurricanes, but all the models show increased sea surface temperatures for $2 \times CO_2$ (Pulwarty and Riehl in Harwell (1990)). For this reason, a hurricane scenario is included as one possible consequence of CO_2 doubling, as hurricanes crossing that region might be more intense and frequent than at present.

Since the response to nuclear winter and $2 \times CO_2$ are quite different in the rainy and dry seasons, and since the rainy season and dry season have different timings in different parts of Venezuela, the scenarios were divided into those for the dry season and those for the wet season at each station. Dry months are defined as those with less than 50 mm of rain during the month, based on the analysis of Venezuelan rainfall by Andressen and Riehl (Harwell, 1990).

Rainfall is modified by increasing the number of rainfall events, not the intensity of each event. The procedure is as follows: Find the largest rainfall event in the month. Select, at random, a day from all the other days in the month without rainfall. Next, assign to that day a rainfall amount equal to the largest value. Continue this procedure until the total monthly rainfall is equal to the prescribed change, using a fraction of the amount of the largest day for the last day added in order to make the total correct. If there are no days left in the month with no rainfall, continue with the day that has the least rainfall, and increase it until it is equal to the largest day. When reducing rainfall, remove days with rainfall starting with the largest. Remove a fraction of the last day, if necessary to reach the correct total.

An alternative way to alter the precipitation is to change each day by the same percentage. In this case, the insolation for each day will be changed by half of the amount (in percent) that the precipitation is changed. It is recommended that this be considered a secondary method, but should be considered since, even though it is not synoptically sound, it is the method used by other groups. This method can serve as a sensitivity test to determine in which cases the method of modifying the precipitation makes a difference.

Insolation: For $2 \times CO_2$, reduce the insolation for the days with modified rainfall by an amount equal to the percent increase in monthly-average rainfall. For the days of a month in which rainfall is not changed, change the insolation by half of the above amount. This is to account for the fact that in a wetter climate, even those days for which precipitation does not change, the cloudiness will change. Two secondary insolation scenarios are: constant insolation as precipitation changes; and as precipitation increases, insolation increases by half that amount for the days when precipitation is changed, and by one fourth that amount on the other days of the month. In the case of deforestation, increase the insolation because of less cloudiness, but not to more than what it would be for clear-sky conditions. Therefore, insolation will be increased by a fixed percentage for each day, with an upper limit. For nuclear winter, the insolation changes will be caused almost exclusively by the smoke in the atmosphere, and will be further modified by changes in the cloudiness. The average insolation changes are thus applied each day of the month.

5. Conclusions

Scenarios have been generated for the most likely climate changes for three different anthropogenic causes of climate change to be used in two different effects assessment models for three different case study regions. These scenarios, combining general information from GCMs with specific information from station observations, illustrate a significantly improved method for scenario generation and provide the most reasonable scenarios possible at this time given the accuracy of the GCMs, for testing the impacts of equilibrium greenhouse warming, deforestation, and nuclear winter. These techniques can be applied to other global change case studies, but will require input from both model and data studies. This is not a procedure that can be automated at this time, since it requires detailed knowledge of the synoptic climatology of a region, which is usually only available from local experts. As an example, the complete reversal of the north-south land/water distribution between the Venezuela case and the Africa case causes very different rainfall regimes, which results in different types of precipitation scenarios. This insight, gained from detailed data studies, is the type of information essential for generating defensible regional scenarios of climate change.

The next step in investigating the impact of these potential climate changes (Table I, step 7) is to use these scenarios in effects assessments to calculate the responses to various climate changes. Extensive sensitivity studies will be required at the same time to explore the dependence of the impact on the scenarios. In addition to the specific scenarios and methodology developed here, a range of arbitrary changes of temperature, precipitation, and insolation, separately and in combination, will have to be used. This broad approach was explicitly used in the China case (Table VI), but must still be done for the other case studies. The specific method of changing certain parameters (e.g., change precipitation in the same way each day, or add rainy days, as in the Venezuela scenarios) will also have to be tested. Some impacts may be insensitive to these details of the specification, and others may depend crucially on them. These calculations are now under way for the case studies in this paper under the PAN-EARTH project, and the results will help to advance our understanding of the human impacts of anthropogenic climate change.

6. Acknowledgments

We would like to thank Steve Ghan for providing nuclear winter simulations, Bill Campbell for producing maps of GCM output, Graham Farmer for providing African rainfall data, and Mike MacCracken for valuable comments. We also acknowledge the contributions of the participants at each of the PAN-EARTH

Workshops on climate change in the case study regions, especially the coordinators of the case studies (Miguel Acevedo, Venezuela; Taye Bezuneh, Africa; and Ma Shijun and Ding Yihui, China). This work was supported by Rockefeller Brothers Fund, Ford Foundation, and the Univ. of Maryland Center for Global Change.

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(Received 26 June, 1991; in revised form 10 November, 1992)