THE RISK MANAGEMENT DILEMMA OF CLIMATE CHANGE

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INTRODUCTION

Human-induced climate change (i.e., "global warming") comprises a risk management dilemma for water managers and policy makers. There is consensus—but not unanimity—in the earth science community that human emissions of "greenhouse" gases, especially carbon dioxide (CO_2), will cause the earth's climate to undergo significant warming in coming decades. Earth scientists, water resources professionals, special interest groups, and the media present conflicting predictions (and images) of climate warming, consequent changes affecting water management, and appropriate responses by water managers and society.

Significant modification of climate, including the hydrologic cycle, could dramatically change the risk setting in which water resources systems are planned and operated. This could be a very potent incentive for anticipatory action on the part of water managers and for preventative action on the part of society at large. However, water managers—like other resource managers—find themselves caught between competing advice, ranging from urgent action to utter dismissal. How can water professionals distinguish fact and fiction and recognize uncertainties that underlie the issues of climate change, as well as the implications for water resources planning and management?

The following discussion will consider water resources management in the context of climate change, organizing the issues into a risk management framework. This framework consists of four major risk elements: (1) risk contexts, (2) risk perception, (3) risk analysis, and (4) risk management. The intent of the discussion is not to provide a comprehensive review of any of the component issues, but rather to consider the issues holistically, promoting the development of pragmatic risk management strategies.

RISK CONTEXTS: CLIMATE CHANGE AND THE POTENTIAL FOR CHANGING RISKS

Water management takes place in a variety of contexts, including physical, socioeconomic, political, environmental, and legal. At the local, state, regional, and national levels, water managers plan and operate complex water management systems with consideration of the uncertainties that characterize the management parameters in these contexts. Some uncertainties have sufficient probability of occurrence and severity of outcome—especially for people who depend on these systems—that they are classified as risks.

The challenge of global warming is that average temperatures are expected to rise rapidly in coming decades. The increasing temperatures could upset energetic balances within the global climate system, perhaps stimulating changes in precipitation or other climate regimes (Hansen et al., 1989). What was once irrelevant for water managers may now require consideration in their operations and planning. In particular, the planning horizons for many water resources systems—often measured in decades—may coincide with significant changes in climate, particularly in the hydrologic cycle.

Climate change researchers are struggling to refine assessments of the character and rate of climate change and its implications for the water cycle (Gleick, 1988; Miller and Russell, 1992). Underlying these efforts are (1) the increases in atmospheric concentrations of CO_2 since 1800 from 275 parts per million by volume (pmv) to 335 pmv today and (2) the expectation that the concentrations will continue to increase at least through the next century. Broad assessments of the implications are possible, but at this time the global climate models are too coarse to provide the regional and local impact assessments that water managers require for operational responses (Cohen, 1991;

Dickinson et al., 1989). In its most recent report, the Intergovernmental Panel on Climate Change (IPCC), an international committee of leading earth scientists assembled by the United Nations and the World Meteorological Organization, reinforced it previous assessment that global warming has occurred, is occurring, and cannot be explained by natural causes (Houghton et al., 1995). The IPCC reports that even if the 1994 level of CO_2 emissions was maintained, a doubling of preindustrial CO_2 atmospheric concentrations (500 pmv) would be expected by the end of the next century.

Climate change could affect the patterns of uncertainty for many different water management parameters. For most water resources professionals, the central issue of climate change is the potential to significantly and rapidly alter the risks of extreme hydrologic events (i.e., floods and droughts). The perceived risks of these events are critical planning and operational parameters for most water management systems. There are some indications that as the hydrologic cycle changes, the frequencies and severities of these events might also change (Mearns, 1993; Rosenburg, 1987; Wigley, 1985). To understand how the risks of extreme hydrologic events might change with climate change, it is necessary to review the fundamental issues of climate change and the status of current climate change research.

Anticipating Climate Change

There has been concern for more than a century that human actions that increase greenhouse gas concentrations might significantly increase global temperatures and thereby trigger further changes in the global climate system by perturbing delicate energy, material, and chemical balances (Arrhenius, 1892). Until the last two decades the means to test such speculations were not available. What we know about climate change comes largely from two sources: paleoclimatic indicators and general circulation models (GCMs). However, the evidence that each of these sources provides is not consistent or unambiguous.

It is possible to anticipate future climate changes by examining how climates have changed in the past. The earth's geologic record holds many indicators of past climates. These include biologic evidence such as tree rings or pollen grains lodged in geologic strata, atmospheric isotopes embedded in the sea floor, and samples of ancient atmospheres trapped in bubbles within glaciers (Pearman et al., 1986).

The climate of the earth has varied widely in the past. These fluctuations are attributed to complex combinations of external and internal climatic forces. Among the most significant "internal" climate forces are the constituents of the atmosphere, the locations of the continents under the influences of plate tectonics, and the amount of land and ocean surface covered by ice. The "external" forces include the radiance of the sun, the earth's orientation relative to the sun, and its orbital path around the sun (Berger et al., 1984).

The strengths of paleoclimatic indicators lie in their abilities to (1) relate internal and external forces to actual climate changes and (2) assess the characteristics and rates of past climate fluctuations (Houghton, 1984). However, they are limited in their spatial and temporal resolution and in the coverage of climatic parameters. In addition, paleoclimatic indicators are poorly suited for predictive analyses. As a result, the principal analytic tools for forecasting climatic changes in the next century are general circulation models (GCMs).

GCMs are extremely sophisticated three-dimensional models of the global climate system. They divide the global atmosphere into a series of horizontal and vertical cells and simulate the dynamics of the climate system as a series of complex energetic and material feedbacks between them. The strengths of GCMs reside in their ability to (1) look forward from the present climate system and (2) control and test a wide variety of climate scenarios.

There are seven state-of-the-art GCMs currently in operation worldwide (Houghton et al., 1990). The GCMs broadly agree that global mean temperatures should rise as a result of the enhanced greenhouse effect. However, the models do not agree about the specific nature and timing of the potential changes, particularly at the regional and local scales. This is due to the complexity of global biogeophysical processes and constraints on the spatial and temporal resolutions of the GCMs imposed by existing computer technology. Nevertheless, in the earth science community there is considerable confidence in the GCMs—at least at the global scale—due in part to their successful simulation of the existing climate with baseline ("Control") climate scenarios (Lamb, 1987). Recognizing these strengths and limitations, the IPCC in 1994 interpreted the collective results of all the GCMs to estimate that with the continued increase in greenhouse gas emissions (i.e., the IPCC's "best estimate"), global mean surface air temperatures could increase 2^0C (4^0F) by 2100 relative to 1990 (Houghton et al, 1995). These warming forecasts were less dramatic than those contained in the IPCC's 1990 and 1992 reports, but in the latest report the IPCC expressed increasing confidence about the likelihood of warming occurring (Houghton et al., 1995).

Implications for Water Management

The GCMs indicate that the hydrologic cycle will intensify with warming and that the hydrologic effects of warming will vary regionally (Houghton et al., 1995). In general, a warmer atmosphere would be able to hold more water. This could increase evaporation rates, thereby reducing streamflows and soil moisture. However, it could also lead to increases in precipitation, at least in some areas. There are also hydrologic implications of continued increases in atmospheric CO_2 besides warming effects. The increased CO_2 could significantly reduce the transpiration rates of many plant varieties by increasing stomatal resistance (Idso, 1991; Woodward, 1987). This could potentially reduce the water demands of many plants (Fajer and Bazzaz, 1992).

To date, most of the investigations into the potential hydrologic impacts have been conducted by modeling hydrologic parameters within the GCMs (Abramopoulos et al., 1989; Entekhabi and Eagleson, 1989; Kellogg and Zhao, 1988; Manabe and Wetherald, 1987). On a global scale, precipitation levels are generally predicted to increase as a result of the above factors. However, this does not imply that more precipitation will occur when or where it is needed by society. For example, the GCMs generally project enhanced precipitation in the tropics and the high latitudes throughout the year and in the mid-latitudes in winter (Houghton et al., 1990).

In the case of the northern U.S., the GCMs generally anticipate little change (or perhaps a slight increase) in winter precipitation and a slight decrease in soil moisture. For the summer, they generally anticipate a significant decrease in both precipitation and soil moisture. The precipitation changes in this region are expected to result from a poleward shift of the mid-latitude rainbelt, which is associated with the most common paths taken by mid-latitude low pressure systems along the jet stream (Wetherald, 1991). The soil moisture decrease in the summer is expected to result from decreased precipitation and increased evapotranspiration from higher temperatures.

Means vs. Extremes

While changes in mean temperature and hydrology could manifest very significant impacts on human and natural systems, extreme hydrologic events might produce the most immediate and significant impacts of climate change (Mitchell and Ericksen, 1991). If climate change occurs, the risks of extreme hydrologic events could be exacerbated. Changes in extreme hydrologic events are even more difficult to assess than changes in mean hydrologic conditions. Droughts and floods as extreme events are by definition statistically infrequent compared to some long-term climatic average. If the mean climates are changing as suggested by the GCMs, consequent alteration of the frequency, severity, duration, or distribution of droughts and floods are likely.

The threats posed by floods and drought to society could increase with climate change. A simultaneous increase in floods and droughts might be possible in the middle latitudes. While precipitation events might occur less frequently due to a reduction in temperature gradients between converging air masses, when they occur more water might be released, since a warmer atmosphere can hold more water. The exposure of society to these extremes may concurrently be exacerbated by (1) larger populations living in areas particularly subject to floods and droughts and (2) inappropriate responses to changing risks, since populations at risk and water managers may be responding to the new conditions based on outdated assumptions. This is equivalent to the adage "the military always prepares for the previous war."

Dissenting Opinions

While there may be a consensus in the earth science community regarding significant human-induced climate warming, there are dissenting opinions which bear recognition. Richard Lindzen of the Massachusetts Institute of Technology and Patrick Michaels of the University of Virginia are two prominent skeptics of the IPCC's climate warming scenarios. These climatologists note that the outputs of the GCMs should be interpreted with caution. While the models are very sophisticated, they are constrained by current supercomputer technology (Lindzen, 1992). These critics also suggest that the greater levels of atmospheric CO_2 may not necessarily translate into higher temperatures. Among the major uncertainties cited are feedbacks (positive or negative) from modified cloud formation (Schlesinger and Roeckner, 1988; Wetherald and Manabe, 1988).

RISK PERCEPTION: INTERPRETING THE POTENTIAL FOR CHANGING RISKS

In the same way that the community of earth scientists contains different perceptions about the prospect of climate change, the water management community encompasses diverse views about its implications for water management. The interpretation of available evidence forms the basis for perceptions of the potential for changing risks of extreme hydrologic events. At the two extremes of this spectrum are advocates of active responses to the potential for changing risks and staunch opponents to any response (U.S. Water News, 1991). The middle of the spectrum is occupied by a variety of positions, including disinterested observers and those who adopt a wait-and-see approach.

Policy studies may provide the most direct risk communication to water managers. Many of these studies urge water managers to recognize the potential for changing risks resulting from climate change and to anticipate which responses might be appropriate (Office of Technology Assessment, 1993; Jacobs and Riebsame, 1989; Waggoner, 1990).

Policy specialists attempt to assess and communicate the risks that climate change may pose for water management. However, their interpretations of climate change research and policy responses can not be directly inserted into management activities, as illustrated in Figure 1. For instance, their risk communications may or may not change the drought risk perception of water managers (Sandman, 1986). Resource managers have an understandable interest in the resources that they are responsible for rather than the hazards that face them (Saarinen et al., 1984).

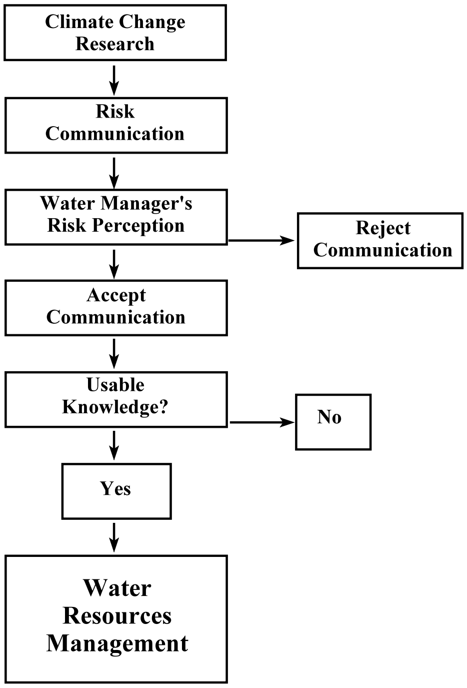

Figure 1
Climate Change Research and Water Management

Even if water managers accept the risk communications, their understanding of the potential for risks to change must be in a usable form before climate change research can affect water management. Ravetz (1986) points out that the reductionist tendencies of the scientific method make it difficult to address problems that are aggregates of many contributory causes and that have unclear temporal and spatial bounds. He also stresses the need for quality control of scientific information in cases where "hard facts are few and far between." Climate change is such a case.

The National Academy of Sciences, in its report The Policy Implications of Greenhouse Warming, suggested that water managers "increase the efficiency of use through water markets and by better management of present systems of supply" (NAS, 1991). This kind of advice is of little help to water managers, since it does not provide appropriate and convincing scientific evidence that informs water managers, nor does it supply useful risk management tools.

In short, the dilemma of climate change facing water managers is the result of uncertain science and vague policy recommendations. The outcome is that despite mounting evidence of the potential for changing risks, water managers continue to make decisions using the traditional assumption that climate is stationary. This behavior should not be surprising given the inertia of many resource management organizations (Sewell, 1971). Evolutionary changes are difficult to institute, much less the potentially radical changes suggested by some climate change scientists and policy analysts.

Assumptions of Stationarity

The acceptance or rejection of risk communications regarding climate change by water managers is a function of their personal and professional perceptions of risk and appropriate responses. Most water managers are accustomed to operating under risk and uncertainty. They regularly face combinations of physical, social, and technological uncertainties that pose risks to people and property, as well as their water systems. Many water managers are also aware that risk patterns are dynamic. For example, land use changes in watersheds can dramatically affect risks of extreme hydrologic events downstream. Nevertheless, the potential for climate change to affect risks of extreme hydrologic events constitutes a fundamental problem for water resources planning and management, since techniques for risk assessment and management assume that climate is stationary for practical purposes.

Estimating the frequency and severity of extreme hydrologic events is a very imprecise science. One reason is that there are limited hydrologic records for North America. Also, extreme events by definition are rare. Nevertheless, there are accepted techniques for estimating the frequency and severity of these extremes. The problems posed by estimating extreme hydrologic events in a changing climate arise not so much from the lack of available techniques as from the implicit assumption of these methods that the climate in the future will be the same as in the past as represented by historic climatic data.

Many water resources planners recognize that climate undergoes long-term changes. However, climatic changes are generally dismissed as too slow to warrant practical consideration. The assumption of stationarity does not imply that climate has no interannual variation. Instead, climatic conditions are perceived as varying about fixed mean conditions. It also implies that the variability around the mean is generally consistent and predictable.

For those managers who accept the potential for changing risks with climate change, they must then decide whether planning or operational responses are required. There would a natural inclination to wait and see if global warming does occur and whether it has any manifestations in the hydrologic cycle. For managers, the marginal costs of responding at this time are relatively certain and potentially high, but the marginal benefits are unknown. In addition, in the future there may be new technologies or information that would allow more cost-effective responses. Unfortunately, the IPCC believes that it will be very difficult to detect climate change as it is occurring (Houghton et al., 1995). There is too much interannual variability to detect long-term changes.

For many managers, it may be a question of priorities. There may be so many short-term management considerations that perceived long-term issues such as climate change may seem inconsequential. Similarly, when managers prioritize their risks, climate change may be distinguished from extreme hydrologic events and relegated to a position far down the list.

Resiliency and Robustness of Water Systems

Water managers may also have an underlying confidence in the resiliency and robustness of water systems as currently planned and operated. Water resources engineers have adopted the vocabulary of robustness and resilience to describe engineering practices for coping with physical and operational vulnerability (Fiering, 1982; Hashimoto et al., 1982). Robustness refers to the insensitivity of system design to errors in the estimates of design parameters. Designs are robust at some level if design parameters lead to a specific design with a given probability level. Resilience is the system's built-in buffering and redundancy such that the operation of the system can be made to compensate for the design error to some degree.

That water managers employ certain criteria of robustness and resilience in the design of supply systems underlines the fact that there already exist some level of planning for coping with extreme events. Climate variability is customarily an assumption of system planners. A significant amount of buffering and redundancy is also usually built into the system. If the assumptions are incorrect, the buffering and redundancy are intended to provide the resilience necessary to cope with unforeseen conditions.

RISK ANALYSIS: ASSESSING THE POTENTIAL FOR CHANGING RISKS

The current dilemma for water managers is that climate change researchers and policy specialists are urging them to prepare for global warming, but neither group offers specific guidelines about the timing, characteristics, or locations of specific climate changes. Climate change research will remain disconnected from water management until (1) there is significant progress in the science of climate change, allowing application of existing decision-making models and/or (2) new decision models that can incorporate existing scientific knowledge are developed.

If water managers are going to respond to the potential for changing risks of extreme events, risk analyses must be conducted at specific locations. These assessments will have to rely on regional hydrologic models that can use GCM outputs either inside or outside the global models.

Multiple hydrologic impact assessments have already been conducted, either within GCMs or by incorporating their outputs. These include (1) national climate change impact assessments (Rind and Lebedeff, 1984; Smith and Tirpak, 1990), (2) regional assessments (Flashka et al., 1987; Gleick, 1988; Morrisette, 1988; Riebsame and Jacobs, 1988), and (3) river basin assessments (Cohen, 1991).

These assessments must be interpreted with caution. The GCMs could be masking elements which would produce greater warming or could be causing over-estimation of the warming to be anticipated. They also do not yet have the spatial resolution necessary for confident incorporation into water management. However, their outputs may serve as an indicator of the types of changes that may occur with climate change. Necessary steps to increase the relevance of GCM outputs for water management are considered below.

GCM Hydrologic Modeling

There is currently a great deal of research taking place on the subject of global climate change, including paleoclimatic research and development of the GCMs. As part of the GCM research, there are ongoing efforts to improve the hydrologic modeling within these models and increase the confidence in the hydrologic outputs of these models.

One of the most critical challenges for linking the outputs of GCMs to regional or local water management is their spatial resolution. Figure 2 illustrates the problem with the spatial coarseness of the models. This figure depicts one cell of the General Fluid Dynamics Laboratory (GFDL) GCM. Even if the GCM outputs were reliable, a single set of climatic changes for an area of this size would be of little practical utility. For this reason, climate change researchers are endeavoring to increase the spatial resolution of these models.

Regional Hydrologic Modeling

The incorporation of GCM outputs into regional hydrologic models would be desirable for four reasons. First, diverse and powerful regional hydrologic models are well-developed. Second, they can be shaped to use GCM outputs. Third, regional models are easier to manipulate and run than the hydrologic algorithms of the GCMs. Finally, the combination will have the flexibility to incorporate refinements of GCM forecasts (Gleick, 1986).

For regional models to utilize GCM outputs, the hydrologic data (e.g., temperature, precipitation, or soil moisture) in a given cell needs to be compared for two scenarios: (1) the Control scenario, which simulates current conditions and (2) the Double CO_2 scenario, which simulates the conditions with a doubling of pre-industrial (i.e., 1800) atmospheric concentrations of CO_2. The changes between the two scenarios can then be applied to current conditions in the region to anticipate the effects of climate change. However, the spatial resolution of the GCMs makes regional or local interpretation of their outputs very problematic (Harrington, 1996).

Risks of Extreme Events

In addition to the problem of spatial resolution, analysis of the changing risks must draw inferences of extreme hydrologic events from GCM outputs that model mean conditions expected with climate change. If the continental—particularly the interior—U.S. is to experience warmer and drier summers with climate change as suggested by some GCM scenarios, drought risks may be exacerbated. However, as layers of interpretation are added to climate change impact studies (e.g., from warming scenarios to hydrologic changes to inferences for extreme hydrologic events) the uncertainties are compounded.

Traditional Risk Analysis Techniques

Traditional risk analysis techniques can shed light on the potential implications of changing risks of extreme events. One technique to assess the levels of hydrologic risk and uncertainty in climate change has been to conduct sensitivity analyses. Specifically, sensitivity analyses can be prepared to assess responses of regional or local hydrology to incremental changes in temperature and precipitation (McCabe and Ayers, 1991). Monte Carlo simulations may be especially appropriate for assessing implications of climate changes for mean and extreme hydrologic conditions.

RISK MANAGEMENT: RESPONDING TO THE POTENTIAL FOR CHANGING RISKS

The scientific understanding of climate change—and potential effects on water management—is clearly evolving. However, the fact that forecasts of climate change are unclear should not be justification for inaction. Pragmatic responses to the potential change of extreme events with climate change are possible—without dismissal of potentially serious risks or reflexive, uniformed responses.

International actions that are designed to slow down the addition of greenhouse gases to the atmosphere are currently driven by the specter of global climate change, but detailed programs of adjustments must be developed by the managers of different water systems at the local level. Depending on the location (climate change is anticipated to affect some regions more than others) and the specifics of the water system, appropriate responses at this time may include: no action, general research, focused research, or planning/operational responses. Potential responses at this time may include:

1. Communication

The water management community should enhance lines of communication with the climate change research community. State climatologists could serve as an excellent intermediary between local water managers and the research community. Some states have initiated climate change research programs to link climate change research and water management. The Climate Change Research Program conducted by the Illinois State Water Survey is an excellent example (Changnon, 1991).

2. Usable Knowledge

As suggested in Figure 1, information about climate change and the potential for changing risks must be in a form that is usable by water managers. It would be particularly important for policy specialists to filter and translate climate change research results for management applications. Standard water management parameters would be most relevant to many water managers. Examples of usable information generated about climate change would include precipitation, streamflow, and/or the Palmer Drought Severity Index.

3. Flexibility

Water resources planners have essentially two choices for responding to the potential exacerbation of extreme events: design systems to meet the worst conditions expected during the life of the project or incorporate sufficient flexibility to modify it as conditions change. There is a current trend in water resources engineering to replace traditional design standards with risk-based designs (Haimes and Stakhiv, 1986 and 1990). Facilities were traditionally designed to meet certain conditions (e.g., a drought of a certain magnitude) with some standard reserve margins added for contingencies and safety.

The intention of risk-based design is to build systems that are appropriate to the risks they face. However, underlying its popularity is its ability to eliminate the costs of overbuilding water resources facilities by increasing the specificity of the design relative to the probability of conditions and need. Risk-based engineering has been heralded as a new generation of design processes. However, risk-based engineering could downsize water resources structures using historical estimates of risk at a time when risks could be rapidly changing. Ironically, the latest design methodologies could increase the vulnerabilities of water resources facilities in the face of increasing risks. There is, however, opportunity in risk-based design if the potential modification of risks by climate change are incorporated in the process.

4. Preparation for Extreme Events

As suggested by Mitchell and Ericksen (1991), the best preparation for the uncertainties associated with resource management in the context of climate change may be to increase preparedness for extreme events. This would allow better coping with expected events and additional resilience in management systems to deal with surprise events in terms of severity, timing, or location.

5. Leadership

Federal and state water management institutions and the professional community of water managers can provide policy guidance to local and regional water managers who are faced with potentially dynamic circumstances in their planning and operations. All of the items mentioned above could be enhanced by focused research and by communications to water managers regarding the prospect of climate change and the potential modification of extreme events. The water management community should confront the risk implications of climate change and begin to develop pragmatic responses to this risk management dilemma.

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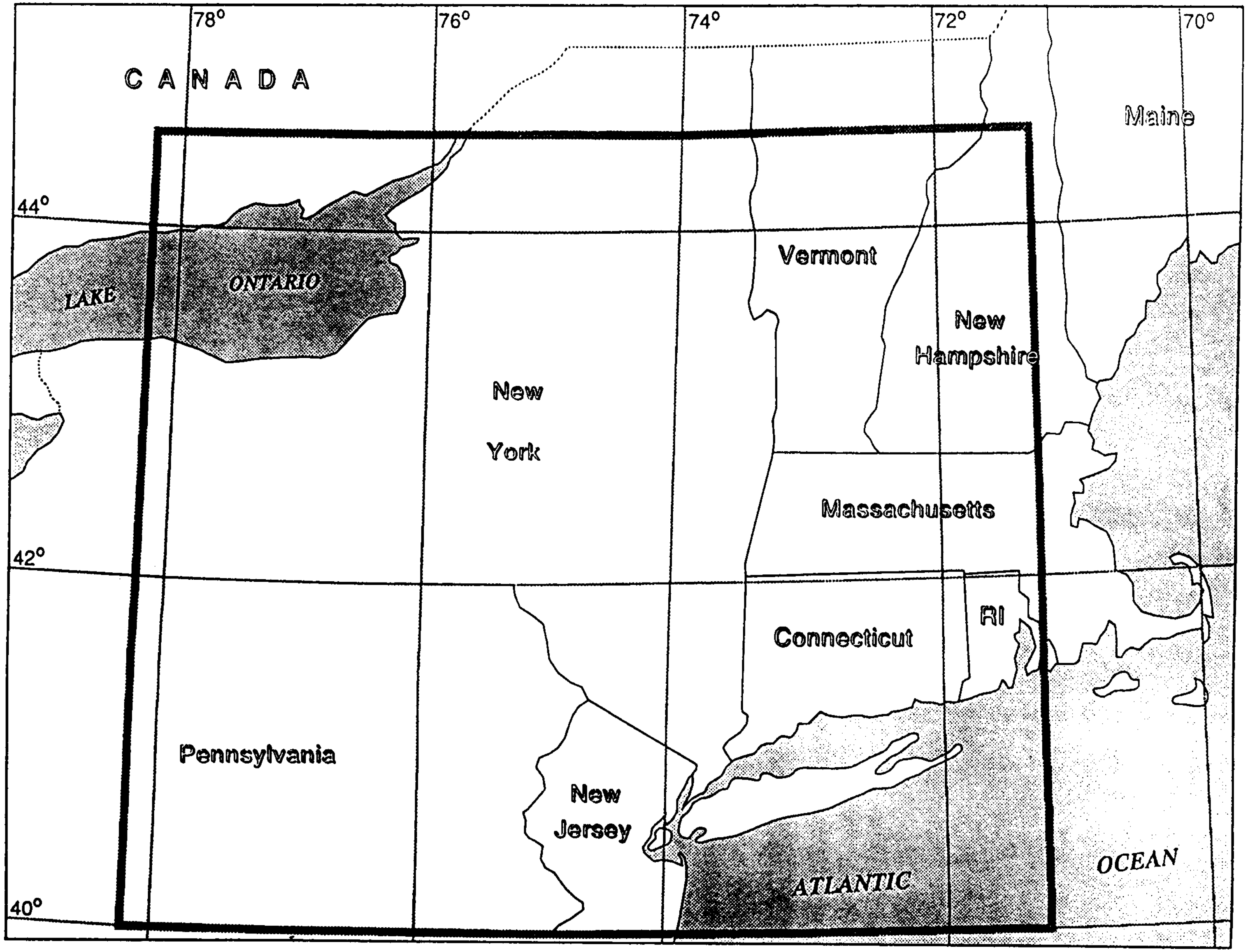

Figure 2
Illustration of a Single GCM Cell