WATER PLANNING AND MANAGEMENT UNDER CLIMATE CHANGE

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BACKGROUND

The debate about whether or not climatic change is a real problem is not over, but the nature of that debate is beginning to change. Instead of arguing about the complex details of atmospheric science and modeling, increasing attention is being given to trying to understand possible consequences for society and the kinds of responses that make sense despite the many remaining uncertainties. This is particularly true in the area of water resources, where many decisions depend explicitly on the assumptions we make about future climatic conditions. Long-term water planning choices, the design and construction of new water-supply infrastructure, agricultural planting patterns, urban water allocations and rate structures, and reservoir operating rules all depend on climatic conditions.

In the past, water planning and management relied on the assumption that the future climate would be the same as the past. All of our water-supply systems were designed with this assumption in mind. We are now, however, on the verge of unintentionally changing our climate through a wide range of human activities, including the emissions of trace gases from our burning of fossil fuels and the destruction of forests. Most of the scientific community believes that global climatic changes are in the offing unless society begins quickly to reduce its emissions of these gases. Indeed, a growing number of scientists believe that some human-induced climatic changes are inevitable. This issue makes it vitally important that those responsible for water planning and management, policymakers, and especially the public begin to think about the implications of climatic change for our water systems. A lot is at stake; water-related infrastructure is extremely expensive to design and build, and it lasts for many years. Systems for storing and delivering clean drinking water and for collecting and disposing of human wastes have largely eliminated water-related diseases in the industrialized world. A substantial amount of our electricity is generated by hydropower facilities. Productive agriculture in many parts of the world depends on reliable irrigation flows. And extreme hydrological events, including both floods and droughts, wreak havoc on lives and property despite our best efforts to prevent them.

There is a broad scientific consensus that global climatic change is a real problem and that it will alter the hydrologic cycle in a variety of important ways (IPCC 1996a,b). But there is little certainty about the form these changes will take, or when they will be unambiguously detected. As a result, while global climatic changes are likely to begin to appear within the next several decades, or even earlier, we are unable as of yet to accurately determine how such changes will affect water-supply systems or water demands. Given these uncertainties, what advice can be given to the water community? This paper describes some approaches that offer the opportunity for water agencies and managers to begin to think about these issues, and even to plan for the kinds of changes that may occur.

[1] Portions of this article appeared in a piece prepared by Peter H. Gleick for the Journal of the American Water Works Association ("Climate Change and Water Resources") in November 1997, and in Chapter 5 of the new book The World's Water 1998-1999 (Island Press, Washington, D.C.).

The scientific evidence for climate change is strong and growing stronger (see articles by Moss and Sales). Beginning in the late 1980s enormous efforts by scientists from many different backgrounds have vastly improved our understanding of the atmospheric system and its behavior. Uncounted peer-reviewed studies, scientific meetings and symposia, and both large- and small-scale research projects in dozens of scientific fields have explored many of the questions we must answer in order to better understand climate. One major piece of this effort is the Intergovernmental Panel on Climate Change (IPCC), a multi-year scientific assessment of climate change under the auspices of the World Meteorological Organization and the United Nations Environment Programme, with the cooperation of over 120 nations and most of the world's leading climatologists. The first IPCC report was released in 1990, a reassessment was released in late 1995, and the third assessment is now in progress. The 1990 study concluded:

"We are certain of the following:

> Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface" (IPCC 1990).

"We calculate with confidence that:

> Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead. The longer emissions continue to increase at present day rates, the greater reductions would have to be for concentrations to stabilise at a given level" (IPCC 1990).

The Intergovernmental Panel on Climate Change (1996b) also stated "freshwater resources in many regions of the world are likely to be significantly affected," and that many current freshwater problems will be made worse by the greenhouse effect. This new report urges water managers to begin "a systematic reexamination of engineering design criteria, operating rules, contingency plans, and water allocation policies" and states with "high confidence" that "water demand management and institutional adaptation are the primary components for increasing system flexibility to meet uncertainties of climate change." This emphasis on demand management rather than construction of new facilities marks a change in traditional water management approaches, which in the past have relied on the construction of large and expensive infrastructure.

Several other major efforts have also explored the implications of climate change for water resources. For example, the Second World Climate Conference, held in Geneva in late 1990, concluded:

> "The design of many costly [water management] structures to store and convey water, from large dams to small drainage facilities, is based on analyses of past records of climatic and hydrologic parameters. Some of these structures are designed to last 50 to 100 years or even longer. *Records of past climate and hydrological conditions may no longer be a reliable guide to the future. The design and management of both structural and non-structural water resource systems should allow for the possible effects of climate change.*" (Italics added) (Jager and Ferguson 1991.)

A separate study of the American Association for the Advancement of Science (AAAS) published in 1990 focused explicitly on the implications of global climate changes for the water resources of the United States. This study, chaired by Drs. Roger Revelle and Paul Waggoner (Climate Change and U.S. Water Resources, J. Wiley and Sons, New York, 1990) concluded:

> "Among the climatic changes that governments and other public bodies are likely to encounter are rising temperatures, increasing evapotranspiration, earlier melting of snowpacks, new seasonal cycles of runoff, altered frequency of extreme events, and rising sea level...*Governments at all levels should reevaluate legal, technical, and economic procedures for managing water resources in the light of climate changes that are highly likely.*" [Italics in original]

In mid-1998, a new assessment of the implications of climate change for the United States (the "National Assessment") was begun. One component of this assessment is a new look at the impacts on water resources, including both hydrology and water management and planning. While no results from this assessment will be available until late in 1999, the effort will bring together water managers and water utility planners with climatologists, hydrologists, and others in the community of water scientists.

SUMMARY OF THE EFFECTS OF CLIMATE CHANGES ON WATER RESOURCES

Among the expected impacts of climatic changes on water resources are higher global and regional temperatures, increases in global average precipitation and evaporation, changes in the regional patterns of rainfall, snowfall, and snowmelt, changes in the intensity, severity, and timing of major storms, and a wide range of other geophysical effects. These changes will also have many secondary impacts on freshwater resources, altering both the demand and supply of water, and changing its quality.

Many uncertainties remain about the timing, direction, and extent of these climatic changes, as well as about their societal implications. These uncertainties greatly complicate rational water resource planning for the future and have contributed to the ongoing debate over how to respond to the problem of climate change. Despite these uncertainties, here is a partial summary of what water managers and hydrologists can expect.

Temperature, Evaporation, and Precipitation

There is a high degree of confidence that global average temperatures will rise as greenhouse gas concentrations rise; indeed, there is already strong empirical evidence that anthropogenic warming has begun. Regional temperatures will also increase, though some areas may experience short-term cooling effects due to the complex behavior of the climate system. Evaporation of water from land and water surfaces will increase as global and regional temperatures rise. More evaporation will result in more precipitation on average, though regional precipitation patterns will continue to be very complex and variable. Reviews of state-of-the-art climate models suggest that global average evaporation and precipitation may increase by 3 to 15 percent for an equivalent doubling of atmospheric carbon dioxide concentration. The greater the warming, the larger these increases.

Over the last two decades, improvements in modeling of the climate have begun to permit more realistic estimates to be made of regional evaporation and precipitation patterns. Increases in precipitation are expected to occur more consistently and intensely throughout the year at high latitudes. With a doubling of atmospheric CO_2 concentrations, models show moister atmospheres (i.e., increases in specific humidity), and greater precipitation in high latitudes and tropics throughout the year and in mid-latitudes in winter. In many of the model estimates, summer rainfall decreases slightly over much of the northern mid-latitude continents. Other changes in mid-latitudes remain highly variable and ambiguous. Information on changes in precipitation in subtropical arid regions is very scanty but even small changes in these arid zones can have significant implications for ecological and human systems. While the intensity of precipitation is very important for water management, little is known about how extremes might change.

Changes in Soil Moisture

Changes in temperature and precipitation patterns will have direct effects on soil moisture, which is critically important for agricultural production and ecological conditions. In regions where precipitation increases, increases in evaporation owing to higher temperatures may be even greater, leading to a net drying of the land surface. One important finding of recent research was that the incidence of droughts in the United States, measured by soil moisture conditions, is likely to dramatically increase as temperatures go up even where precipitation increases, because of increased evaporation (Rind *et al.,* 1990). This finding has also been seen in some of the detailed hydrologic modeling of specific river basins, such as the Colorado, where large increases in precipitation may be necessary in order to simply maintain river runoff at present historical levels as temperatures and evaporative losses rise (Nash and Gleick 1991).

All climate model results simulate a general increase in soil moisture at the high northern latitudes in winter where precipitation increases exceed evaporation increases. Most models also simulate large-scale drying of the Earth's surface over northern mid-latitude continents in northern summer owing to higher temperatures and either insufficient precipitation increases or actual reductions in rainfall. Drying in these regions could have significant impacts, particularly on agricultural production and water demand.

Changes in Snowfall and Snowmelt

One of the most important hydrologic impacts of climatic change will be snowfall and snowmelt changes in high-altitude watersheds or areas with strong snowmelt runoff characteristics. In these watersheds, changes in temperature are expected to lead to important changes in water availability and quality and complicate the management of reservoirs and irrigation systems.

In basins with substantial snowfall and snowmelt, temperature increases will have three effects. They increase the ratio of rain to snow in cold months, they decrease the overall duration of snowpack season, and they increase the rate and intensity of warm season snowmelt. As a result of these three effects, average winter runoff and average peak runoff increase, peak runoff occurs earlier in the year, and there is a faster and more intense drying of warm-season soil moisture. Because of these effects, far more attention needs to be paid in some regions to the risk of floods, rather than droughts. One of the greatest concerns about the effect of higher temperatures is, therefore, the increased probability and intensity of flood flows. Earlier snowmelt will also have implications for reservoir storage capacity and operation, and for the availability of stored water for domestic and agricultural use later in the year.

Changes in Storm Frequency and Intensity

Many of the most severe societal impacts resulting from the hydrologic cycle occur due to climatic extremes. An important, but unresolved question, therefore, is what global climatic changes may do to the variability of climatic conditions -- i.e., the frequency and intensity of extremes. Although little work has been done on this issue, there are some indications that the variability (interannual standard deviation) of the hydrologic cycle increases when mean precipitation increases and vice-versa. In one model study the total area over which precipitation fell over the earth decreased, even though global mean precipitation increased (Noda and Tokioka 1989). This implies more intense local storms and runoff.

Other changes in variability are also likely, though at this point we have little confidence that we can predict what they will be. There are some indications that day-to-day and interannual variability of storms in the mid-latitudes will decrease. At the same time, there is evidence from both model simulations and empirical considerations that the frequency, intensity, and area of tropical disturbances may increase. Far more modeling and analytical efforts are needed in this area.

Changes in Runoff

Many estimates of changes in runoff due to climatic change have been produced using detailed regional hydrologic models of specific river basins and a variety of climate scenarios (see Arnell 1996 for a summary). By using expected changes in temperature and precipitation, these models permit the incorporation of realistic small-scale hydrology and suggest that some significant changes in the timing and magnitude of runoff are likely to result from quite plausible changes in climatic variables.

For example, studies of basins in the western United States and elsewhere over the past decade suggest that temperature increases on the order of 2 to 4 degrees Celsius, with no change in precipitation, can result in decreases in runoff of 20 percent or more (Nemec and Schaake 1982, Gleick 1987a,b, Flaschka *et al.*, 1987, Lettenmaier and Gans 1990, Nash and Gleick 1993, Burns 1994, Mimikou *et al.*, 1991). Increases or decreases of precipitation of 10 and 20 tend to change runoff by about the same amount. In basins where demands for water are close to the limit of reliable supplies, such changes will have enormous policy implications.

There is also a risk of increased flooding. The authors of the 1995 IPCC report conclude that the "flood related consequences of climate change may be as serious and widely distributed as the adverse impacts of droughts."

> "There is more evidence now that flooding is likely to become a larger problem in many temperate regions, requiring adaptations not only to droughts and chronic water shortages, but also to floods and associated damages, raising concerns about dam and levee failure" (IPCC 1996b).

Ironically, some regions may experience increases in both droughts and floods if climate becomes more variable. In the western United States, for example, where winter precipitation falls largely as snow, higher temperatures will increase the amount of rain and decrease the amount of snow, contributing to high winter and spring runoff -- the period of time when flood risk is already highest. At the same time, summer and dry-season runoff will decrease because of a decline in snowpack and accelerated spring melting.

SOCIETAL IMPACTS OF CHANGES IN WATER RESOURCES

The climatological and hydrological impacts of climate change on water-resources supply and availability will have direct and indirect effects on a wide range of institutional, economic, and social factors. Just as the scientific implications of climate change are incompletely known, the subsequent societal effects are not well understood, nor do we fully understand the ability of society to adapt to them. Yet arguments about "adaptation" or "coping" have become central to arguments about the costs and benefits of trying to reduce greenhouse gas emissions. If water managers and planners can easily and cheaply cope with any climatic disruptions that may occur, actions to prevent climate change will be less urgent. If we overestimate our ability to cope, or underestimate the scope of the changes that will occur, we may ignore inexpensive and successful actions that can reduce the impacts of climate change early.

Adaptation and innovative management will certainly be a useful and necessary response to climatic changes. Several factors, however, suggest that relying solely, or even principally, on adaptation may prove a dangerous policy. First, the impacts of climate change on the water sector will be very complicated and at least partly unpredictable. Second, many impacts may be non-linear and chaotic, characterized by surprises and unusual events. Third, climatic changes will be imposed on water systems that will be increasingly stressed by other factors, including population growth, competition for financial resources from other sectors, and disputes over water allocations and priorities. Finally, some adaptive strategies may help mitigate some adverse consequences of climate change while simultaneously worsening others.

There is a rapidly growing literature about the impacts of climate change on water systems, reservoir operations, water quality, hydroelectric generation, navigation, and other water-management concerns. At the same time, this literature has barely scratched the surface of the potential range of impacts, and far more research is needed. One consistent finding is that water-supply systems are sensitive to changes in inflows and demands. Nemec and Schaake (1982), in one of the earliest studies on climate impacts, showed that large changes in the reliability of water yields from reservoir systems result from small changes in reservoir inflows. This finding has now been reproduced in many studies from many different regions (Cole *et al.*, 1991; McMahon *et al.*, 1989; Mimikou *et al.*, 1991; Nash and Gleick 1993). In the Mesohora reservoir in Greece, a 10 percent decrease in precipitation leads to a tripling of the risk that the hydroelectric facility there will be unable to produce its design power (Mimikou *et al.*, 1991). In a comprehensive analysis of the Colorado River Basin, the highly integrated system of linked reservoirs was shown to be very sensitive to both the physical characteristics of the system and to the way it is managed and operated. Under current operating conditions and rules, even the extremely large volume of storage in the basin protects against modest climate-induced reductions in runoff for only a few years before the reservoirs are drawn down and hydroelectric generation drops (Nash and Gleick 1991, 1993). A 10 percent decrease in average natural flow in the Colorado River Basin – a plausible result given current climate projections – would result in a 30 percent decrease in reservoir storage, a 30 percent decrease in hydroelectricity generation, and a violation of salinity standards in the lower river in almost all years.

Because of conflicts between flood-control functions and hydropower objectives, climatic changes in California may require more water to be released from California reservoirs in spring to avoid flooding. This would result in a reduction in hydropower generation and the economic value of that generation. The IPCC reports that an increase in fossil-fuel use of 11 percent would be required to meet the same energy demands in California at a cost of hundreds of millions of dollars and a worsening of greenhouse-gas emissions (IPCC 1996b).

In a study of the impacts of possible climatic changes on river temperatures, Miller *et al.*, (1993) concluded that the Tennessee Valley Authority would be forced to reduce power generation and shut down fossil and nuclear plants more frequently to avoid violating temperature standards set for regional rivers. Plant efficiencies, which depend in part on the temperature of cooling water, would be reduced and expensive cooling towers required more often.

This selection of studies represents only a small portion of the work that has been done in the past decade. But almost all of these studies support two important conclusions: first, existing systems tend to be optimally designed for current climatic conditions and to be sensitive to any changes in those conditions; and second, changes in operating rules need to be closely examined to see whether they can reduce the risks associated with fixed infrastructure and designs.

CONCLUSIONS AND RECOMMENDATIONS FOR WATER MANAGERS

Impacts of climate change on water resources will be felt in virtually every aspect of natural resources management. All decisions about long-term water planning, the design and construction of new water-supply infrastructure, the type and acreage of crops to be grown, urban water allocations and rate structures, reservoir operation, and water-supply management depend on climatic conditions and what humans do to respond and adapt to those conditions.

In the past, water planning and management relied on the assumption that future climatic conditions would be the same as past conditions, and all our water-supply systems were designed with this assumption in mind. Dams are sized and built using available information on existing flows in rivers and the size and frequency of expected floods and droughts. Reservoirs are operated for multiple purposes using the past hydrologic record to guide decisions. Irrigation systems are designed using historical information on temperature, water availability, and soil water requirements.

Many uncertainties remain about the timing, direction, and extent of these climatic changes, as well as about their societal implications. Indeed, the most important effect of climatic change for water systems will be to greatly increase the overall uncertainty managers face. These uncertainties greatly complicate rational water-resource planning and have contributed to the ongoing debate over how to respond (see, for example, Frederick, Major, and Stakhiv 1997). But we cannot let these uncertainties paralyze us and stop rational and thoughtful actions from being taken. There are three possible avenues managers can pursue now: the current "wait and see" or the "do nothing" approach, which is cheapest in the short-term but which could have enormous medium- and long-term risks; "no regrets" analysis, which includes evaluating **management and operational** options under a broader range of climate scenarios than managers usually think about; and designing and building new infrastructure to deal with greater climatic uncertainty. This last option runs the risk of making expensive, incorrect design decisions. To help water managers and planners think about these issues, the American Water Works Association recently published a set of recommendations (AWWA 1997). In particular, they concluded that:

> While water management systems are often flexible, adaptation to new hydrologic conditions may come at substantial economic costs. Water agencies should consider re-examining engineering design assumptions, operating rules, system optimization, and contingency planning for existing and planned water-management systems under a wider range of climatic conditions than traditionally used.
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> Water agencies and providers should explore the vulnerability of both structural and non-structural water systems to plausible future climate changes, not just past climatic variability.
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> Governments at all levels should re-evaluate legal, technical, and economic approaches for managing water resources in the light of possible climate changes.
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> Cooperation of water agencies with leading scientific organizations can facilitate the exchange of information on the state-of-the-art thinking about climatic change and impacts on water resources. Among the organizations and activities relevant to these issues are the World Climate Research Programme of the World Meteorological Organization, the Global Energy and Water Cycle Experiment (GEWEX) of the International Council of Scientific Unions (ICSU), the American Geophysical Union, the American Association for the Advancement of Science, the various National Academy of Sciences in leading countries, and many specific research activities such as the work of CSIRO in Australia, the U.S. Global Change Office, and others. In the United States, agencies such as NASA, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey, the U.S. Army Corps of Engineers, and the U.S. Environmental Protection Agency often play an important international role in research on these issues.
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> The timely flow of information from the scientific global change community to the public and the water-management community would be valuable. Such lines of communication need to be developed and expanded.

None of these recommendations requires expensive, difficult changes or actions. But they permit us to better understand the vulnerability of our different water systems and the possible range of actions that might help us reduce these vulnerabilities and risks in the future.

REFERENCES

Arnell, N. 1996. *Global Warming, River Flows and Water Resources*. John Wiley and Sons, Chichester, UK.

American Water Works Association. 1997. "Climate Change and Water Resources." Committee Report of the Public Advisory Forum. *Journal of the American Water Works Association*, Vol. 89, Issue 11, pp. 107-110.

Burn, D.H. 1994. "Hydrologic Effects of Climatic Change in West-central Canada." *Journal of Hydrology*, Vol. 160, pp. 53-70.

Cole, J.A., S. Slade, P.D. Jones, and J.M. Gregory. 1991. "Reliable Yield of Reservoir and Possible Effects on Climatic Change." *Hydrological Sciences Journal*, Vol. 36, pp. 579-597.

Flaschka, I.M., C.W. Stockton, and W.R. Boggess. 1987. "Climatic Variation and Surface Water Resources in the Great Basin Region." *Water Resources Bulletin*, Vol. 23, No. 1, pp. 47-57.

Frederick, K.D., D.C. Major, and E.Z. Stakhiv. 1997. "Special Issue: Climate Change and Water Resources Planning Criteria." *Climatic Change*. Volume 37, No. 1.

Gleick, P.H. 1987a. "The Development and Testing of a Water-balance Model for Climate Impact Assessment: Modeling the Sacramento Basin." *Water Resources Research*, Vol. 23, No. 6, pp. 1049-1061.

Gleick, P.H. 1987b. "Regional Hydrologic Consequences of Increases in Atmospheric Carbon Dioxide and Other Trace Gases." *Climatic Change*, Vol. 10, No. 2, pp. 137-161.

Gleick, P.H. 1998. The World's Water 1998-1999 (Island Press, Washington, D.C.).

IPCC. 1990. *Climate Change*. The IPCC Scientific Assessment. J.T. Houghton, G.J. Jenkins, and J.J. Ephrauns (editors). Cambridge University Press, Cambridge, UK.

IPCC. 1996a. *Climate Change 1995: The Science of Climate Change*. Summary for Policymakers. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

IPCC. 1996b. "Hydrology and Freshwater Ecology." In *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change*. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jager, J. and H. Ferguson. 1991. *Proceedings of the Second World Climate Conference*, Geneva, Switzerland.

Lettenmaier, D.P. and T.Y. Gan. 1990. "Hydrologic Sensitivities of the Sacramento-San Joaquin River Basin, California, to Global Warming." *Water Resources Research* 26, pp. 69-86.

Lettenmaier, D. P., E.F. Wood, and J.R. Wallis. 1994. "Hydro-climatological Trends in the Continental United States 1948-1988." *Journal of Climate*, Vol. 7, pp. 586-607.

McMahon, T.A., R.J. Nathan, B.L. Finlayson, and A.T. Haines. 1989. "Reservoir System Performance and Climatic Change." In G.C. Dandy and A.R. Simpson (eds.) *Proceedings of the National Workshop on Planning and Management of Water Resource Systems: Risk and Reliability*. Canberra. Australian Government Publishing Service, Canberra, Australia. pp. 106-124.

Miller, B.A., V. Alavian, M.D. Bender. 1993. "Impacts of Changes in Air and Water Temperature on Thermal Power Generation." In R. Herrmann (editor). *Managing Water Resources During Global Change*. Proceedings of the International Symposium of the American Water Resources Association, Bethesda, Maryland, pp. 439-448.

Mimikou, M., P.S. Hadjisavva, Y.S. Kouvopoulos, and H. Afrateos. 1991. "Regional Climate Change Impacts: II. Impacts on Water Management Works." *Hydrological Sciences Journal*, Vol. 36, pp. 259-270.

Nash, L.L. and P.H. Gleick. 1991. "The Sensitivity of Streamflow in the Colorado Basin to Climatic Changes." *Journal of Hydrology*, Vol. 125, pp. 221-241.

Nash, L.L. and P. H. Gleick. 1993. *The Colorado River Basin and Climatic Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation.* U.S. Environmental Protection Agency, EPA230-R-93-009, Washington, D.C. 121 pp.

Nemec, J. and J.C. Schaake. 1982. "Sensitivity of Water Resource Systems to Climate Variation." *Hydrological Sciences Journal*, Vol. 27, pp. 327-343.

Noda, A. and T. Tokioka. 1989. "The Effect of Doubling the CO_2 Concentration on Convective and Non-convective Precipitation in a General Circulation Model with a Simple Mixed Layer Ocean." *Journal of the Meteorological Society of Japan*, Vol. 67, pp. 1055-1067.

Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy. 1990. "Potential Evapotranspiration and the Likelihood of Future Drought." *Journal of Geophysical Review.* Vol. 95, pp. 9983-10004.

Waggoner, P. editor (1990) *Climate Change and U.S. Water Resources.* J. Wiley and Sons, Inc., New York.

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