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ABSTRACT

Contained are 15 papers which identify specific areas for research in human uses of the atmosphere and are designed to foster and stimulate interest in these problems among both social and physical scientists. The papers are a preliminary attempt to cope with the complex social, economic, and legal aspects of modifying the weather. Included is an extensive bibliography of literature since 1957. (PR)

HUMAN DIMENSIONS of the ATMOSPHERE

FEBRUARY, 1968

NATIONAL SCIENCE FOUNDATION

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PREFACE

In 1964 the National Science Foundation (NSF) appointed a Special Commission on Weather Modification to examine the physical, biological, legal, social, and political aspects of the field and make recommendations concerning future policies and programs. The report of the Special Commission, submitted in December 1965, concluded that "The need is great to assess more fully the social implications of weather and climate modification" and recommended a greatly increased research effort on the social, economic, and legal dimensions of weather modification.

As a follow-up step in this direction, a 13 man Task Group on Human Dimensions of the Atmosphere was formed in 1966 with representatives from the fields of economics, geography, sociology, political science, law, ecology, and meteorology. The objective of the Task Group was to identify specific areas for research in human uses of the atmosphere and to foster and stimulate interest in these problems among both social and physical scientists. To aid these purposes, the National Center for Atmospheric Research (NCAR) at Boulder, Colo., sponsored the Task Group with financial support from NSF.

The Task Group convened four times for discussion and work sessions. They also received advice from specialists in these areas and sought the views of representatives of both industry and government. Members of the Task Group then prepared articles on the various areas that they had discussed.

Although the individual papers represent only preliminary attempts to cope with the complex social, economic, and legal aspects of modifying the weather, the combined papers represent a pioneering product by the Task Group. As such, these papers deserve to be brought to the attention of all who have an interest in weather modification to serve as a basis for discussion and to stimulate further investigation. It is with this aim that the NSF is pleased to publish this document without any implied endorsement or rejection of any of its contents.

Each of the members of the Task Group and the consultants and representatives who contributed to the Task Group are commended for their efforts.

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The Problem in Perspective

Atmospheric resources are most vital to man, for without the air, warmth, and precipitation which they provide, all life on earth would cease to exist. Until recently, man was able to take these resources for granted, treating them as a free good available for anyone to use for whatever purpose he desired. Generally, one man's use did not seriously interfere with other men's uses. In recent years, however, this situation has changed dramatically: Man's increasing use of the atmosphere for waste disposal has created the problem of pollution; and the development of weather modification technology has raised issues of how benefits are to be distributed and losses compensated.

Pollution of the atmosphere has already become a major problem in several parts of the United States, and the situation is rapidly deteriorating in many others. A National Academy of Sciences Committee on Pollution estimated recently that some 125 million tons of waste materials are poured into the atmosphere each year by the nation's homes, factories and automobiles. Almost every major city in the United States is cloaked in a blanket of smoke, and this pollution is causing huge property losses and health problems. In addition, an affluent society is setting increasingly higher goals for the quality of its environment. Men, therefore, are beginning to ask how far pollution of the atmosphere should be allowed to continue. Should men control the use of the atmosphere just as they control the use of other resources? Should not those who benefit from special measures to control the atmosphere be required to compensate those who suffer losses?

Man's increasing ability to modify the weather raises questions of public policy. It is evident that benefits can be derived from the modification of the weather, either by reducing weather-caused losses of property or income, or by improving production possibilities. It is also clear, however, that the impact of a given alteration in the weather often spreads beyond those who wish to have the weather modified. Several questions of public policy arise as a result. How far should we go in trying to alter the atmosphere? Should those who gain from weather modification be forced to compensate those who lose? If so, on what basis may compensation be arranged? Should weather modification activity be controlled? If so, what mechanisms should be employed for this purpose? Are present laws and administrative arrangements adequate to handle the problems that will result from an increasing ability to modify the weather, such as conflicts among individuals, states and nations?

These questions provided a central focus for the studies of the recent Special Commission on Weather Modification. None of the questions, however, are simple; and while the Commission made broad recommendations relating to each of them, it also noted that much more study is required before satisfactory answers can be given to some questions. In this connection, the Commission called for a greatly increased research effort on the human dimensions of weather modification.

The Task Group on the Human Dimensions of the Atmosphere

The Special Commission on Weather Modification concluded that not only was the present research effort on the economic, social and institutional aspects of weather modification extremely small, but also an increase in the size of that effort would be unlikely unless something were done to encourage social scientists to turn their attention to these problems. Toward this end the National Science Foundation decided to establish a Task Group to determine ways in which research on the human dimensions of weather modification might be encouraged, and to outline the types of research most urgently required.

The National Center for Atmospheric Research (NCAR) at Boulder, Colorado offered to sponsor the Task Group through its Program on Applications Analysis. It was thought that such sponsorship would encourage the Group's interaction with physical scientists engaged in atmospheric research, and that those at NCAR involved in applications of research results might benefit from interaction with those in other fields interested in weather problems. The National Science Foundation accepted NCAR's proposal and furnished the funds to sponsor the Task Group. The Group was designated the "Task Group on Human Dimensions of the Atmosphere."

It was anticipated that the Task Group would focus most of its attention upon weather modification, both because the Group had been established as an outcome of the Special Commission's work, and because several of its members had been engaged in research in this field. However, a broad perspective was maintained throughout. As well as examining problems related to weather modification, the Group considered other alternative adjustments to variations in the atmosphere, and problems related to the increasing use of the atmosphere.

The Task Group was composed of 13 members drawn from the social, natural, and physical sciences. It included representatives from economics, geography, sociology, political science, law, ecology and meteorology. Liaison with NCAR was maintained both through membership in the Task Group and through the attendance of NCAR representatives at Group meetings. Liaison was also maintained with the National Science Foundation through the attendance of two representatives as observers at the meetings.

The Task Group held four meetings, two at NCAR, and two at the University of California, Santa Barbara. Members exchanged information and ideas, and developed an overview of weather modification problems and the ways in which they might be handled. The Task Group benefited from the advice of a number of specialists on particular issues, and from the comments and suggestions offered by representatives of industry and several federal agencies. A list of the various advisors, government agency representatives, and private individuals who contributed to our work appears at the end of this report. The Task Group wishes to thank each of them for his assistance.

Major Questions Facing the Task Group

The work of the Task Group called for investigation of four major questions:

1. What are the principal economic, social, and institutional problems raised by man's increasing use of the atmosphere and by his increasing ability to modify it?
2. What research has been done so far on these problems?
3. What research remains to be done, and what priorities should be assigned to future research efforts?
4. How can needed research be encouraged and promoted?

This report presents the conclusions and recommendations of the Task Group as a whole on these four topics. Detailed discussions appear in the reports of individual members, as appendices to this report.

Human Adjustment to the Atmosphere

Weather and climate present man with a challenge. He can either accept temperature, precipitation and wind as given, and adjust his activities to accommodate these elements; or he can try to alter the processes which produce weather and climate. For the most part man has chosen the former course of action. He has moved to those climatic regions most acceptable for human comfort and the pursuit of various economic activities; and he has taken various measures to accommodate changes in the weather.

Two major types of action have been taken as typical adjustments to the weather: the adoption of techniques which insulate activities from variations in the weather—such as air conditioning, home heating furnaces, storm windows, drought-resistant crops; and temporary alterations in patterns of activity—such as modification of harvesting schedules, postponement of vacations, temporary movements from an area (as in the case of evacuation from the path of a hurricane). Summaries of weather data have been used in making decisions about locating activities (e.g., manufacturing industries). Weather forecasts have been used in making decisions about alterations in activity patterns or movements from potential disaster areas. More recently, techniques have been developed that may be effective in modifying the weather, and this offers man another means of adjustment.

The Modern Scientific Era of Weather Modification

Although attempts to alter the weather have been made since the dawn of civilization, claims of success have always been regarded with some skepticism. Many early attempts were based more on superstition and conjecture than on scientific principles. This was natural because little was known about the processes which produce weather, and the means to verify whether a claimed alteration had in fact been achieved, were lacking. In the past 30 years, however, the rapid accumulation of knowledge about the atmosphere, together with advances in methods of statistical analysis and developments in computer and radar technology, has made possible a much more scientific approach to weather modification. Some uncertainty about man's ability to modify the weather still remains, but the attitude of scientists in this regard seems to be changing. Thus, although the 1957 report of the President's Advisory Committee on Weather Control aroused considerable debate among meteorologists as to the validity of its conclusions on precipitation augmentation, the two recent reports of the Special Commission on Weather Modification and the NAS–NRC Panel on Weather and Climate Modification, which reached broadly similar conclusions on this matter, have aroused only minor debate among meteorologists.

Scientists now generally agree that under certain circumstances precipitation can be increased from winter orographic storms, and cold fogs dispersed. Evidence of success in suppressing lightning and hail is less conclusive, but recent experimental results suggest that ways will soon be found to accomplish these types of modification as well. The prospects of finding ways to alter the tracks of major storms, such as hurricanes and tornadoes, or to modify global circulation patterns, however, appear remote.

It seems likely that there will be major expansion of weather modification activity in the next few years. Commercial firms have taken the conclusions of the two panels on weather modification as an endorsement of their claims of successful operations in the field. This trend is likely to stimulate further commercial weather modification activity. However, much remains to be done in perfecting techniques of weather modification. Accordingly, the Federal Government has embarked upon a large-scale program of research and development, with a view to supporting operational programs. The National Science Foundation is expanding its support of research in this field. The Bureau of Reclamation, the Department of Agriculture, and the Environmental Science Services Administration (ESSA) are also increasing efforts to develop techniques for modifying the weather.

Some Questions Raised by Weather Modification

Do the Benefits Exceed the Costs?

It is apparent from the rapid growth of weather modification activity during the past 20 years that those involved in this effort perceive important benefits from it. Several advantages are claimed for weather modification.

It is generally fairly cheap, and the equipment involved can be moved from one location to another without great difficulty. Many farmers, for example, regard cloud seeding as an inexpensive gamble. If it succeeds in increasing precipitation (or reducing hail), it may make the difference between having a crop or no crop at all. If the effort fails, the investment will not have been large, and more often than not it can be shared among several farmers. Electric power companies that have undertaken programs to increase precipitation believe that the effort is an economical way of improving their operating efficiency. The gains from lightning suppression and from cold fog dispersal are also believed to be substantial.

Identifying the benefits and costs of the use or modification of atmospheric resources is not a simple matter. The dynamic nature and common property characteristics of the atmosphere lead inevitably to external effects. For example, no means have yet been found to confine the effects of using the atmosphere for waste disposal only to the users. Nor have means been found to confine the effects of modifying the weather to those who desire the modification. One farmer may need additional moisture, but his neighbor may suffer considerable losses if such moisture falls on his land too. Similarly, the precipitation which enables the hydro-electric power company to increase its profits may also ruin the vacation of the tourist. These external effects are not always harmful. In some cases, those who do not contract for weather modification may benefit from its results and may therefore experience windfall gains.

A complete evaluation of weather modification requires the identification of activities directly or indirectly affected by weather changes, and an analysis of the manner in which given changes result in gains or losses to such activities. A similar approach is required to determine gains and losses for different areas. In certain weather modification cases, for example, gains in local areas may be offset by losses in other areas.

Any evaluation of weather modification must also take into account that this effort is only one means of attaining specified objectives. Increases in food production, for example, may be obtained in many ways other than by augmenting precipitation in the arid West. Increases in hydro-electric energy production can be obtained not only by cloud seeding, but also by developing thermal power or nuclear power, or by devising inter-connections between power systems. The merits of weather modification, therefore, must be compared with those of alternatives in order to determine the most efficient means of achieving the desired objective.

What is the Potential Impact on Biological Systems?

Another important question raised by the expansion of weather modification activity relates to the potential impact on biological systems. Lack of moisture is the principal factor limiting the biological productivity of much of the earth; and added precipitation in water-short regions can doubtless increase yields of food and fiber from rangelands, forests, and cultivated croplands. However, such major weather modifications may also alter the balance among species of plants and animals—with sharp declines in the numbers of some, and inordinate growth in the abundance of others. In particular, major weather changes may result in the rapid spread of certain weeds, pests, and vector-borne diseases.

Plans for expanding weather modification must therefore take into account the possibility that the benefits of increased range, forest, and crop production will be counterbalanced in whole or in part by undesirable long-term effects on man's sources of food supply, his health, and his general environment. It is particularly important to identify those aspects of weather modification that are likely to have irreversible long-term consequences not foreseen by those whose primary objective is immediate increase in agricultural production or water supply.

Does Everyone Favor Weather Modification?

Another question is that of public acceptance of weather modification. Is everyone in favor of attempts to modify the weather? Experience suggests that although many people in a community may welcome such attempts, others may openly oppose them and may succeed in preventing further modification activity. Opposition may come from those who feel that they may be harmed economically by artificially induced changes in the weather. Opposition may also be much more deeply rooted: some people may feel that it is wrong to tamper with Nature, or that no man has the right to interfere with another man's weather.

Experience has shown that although most attempts to modify the weather go unnoticed, the coincidence of an abnormal weather event, such as a flood or a prolonged period of rainfall, with an attempt at weather modification tends to raise a public outcry against such activity. Lengthy scientific explanations of the lack of association between the two events often prove to be of no avail. Much remains to be done to determine how people perceive the weather, what their attitudes are toward weather modification, and what role information appears to play in conditioning such attitudes.

Should Losers be Compensated?

The fact that there are gainers and losers as a result of weather modification activity gives rise to still another question. What mechanisms exist for compensating those who lose? Thus far the approach has been for those who feel they have suffered a loss from the modification attempts of others to take the matter to the courts. However, inability to prove specific cause and effect for the undesired changes has resulted in no judgments being made about compensation. Even if such proof is available, a problem remains as to what principles should be applied in deciding how much compensation should be paid, and by whom. Should compensation be demanded only from those who ordered the weather modification to be undertaken, or should it be demanded from all those who benefited in some way from the change?

Are Present Legal Theories Adequate?

Are the principles underlying present legal theories of liability appropriate to cases of weather modification? This basic question has been the subject of academic discussion, but no definite conclusions have yet emerged. The general view seems to be that no urgency for answers exists so long as it remains impossible in specific cases to prove that the weather has in fact been modified, and in ways to cause particular results. However, the ability to modify the weather on a more consistent basis is rapidly developing; and as this capability grows, the problem of proving occurrence and cause diminishes. Therefore, principles for compensating losses in weather modification cases will have to be determined. Principles need to be developed not only for settling claims of individuals against other individuals, but also for handling cases of individuals against governments, governments against governments, and perhaps nations against other nations.

What Types of Control Are Required, and What Role Should Government Play?

The fact that weather modification efforts are increasing and that these activities have important external effects makes it inevitable that some form of governmental control will be required. What types of control are needed? Is it sufficient to require licensing of operations, or is it also necessary to require that information on results be furnished? At what level of government should control be vested? Should regulation be in the hands of local, State, or Federal authorities? Should the Federal Government control only those weather modification attempts that might affect more than one State, or other countries—and leave control of other modification activities to State and/or local authorities? Who should determine whether or not an attempt should be made to alter the track of a major storm? A hurricane, for example, might be headed for a large urban area, with a population of perhaps two million people. It might be possible to divert the storm away from that area, thus avoiding millions of dollars of property damage and perhaps major losses of life as well. Such a diversion, however, might be accomplished only at the cost of some property damage and loss of life elsewhere. Similar questions of social equity arise when decisions have to be made about breaking dikes to relieve pressure downstream; and such cases are handled by operating agencies. Can decisions about modifying major storms, however, be left to operating agencies, or should they be placed in the hands of the President and his advisors?

Another set of problems relates to the role that the Government ought to play in the management of atmospheric resources. Should this role be confined to the regulation of the use of these resources, or should it extend to direct participation in development, as in the modification of the weather? Are there particular characteristics of atmospheric resources and their management that call for government participation in development in the same way that certain characteristics of water resources call for such participation? In the case of water resources, the existence of indivisibilities, externalities, and the demand for certain public benefits (such as flood control and municipal water supplies) leads to public intervention and participation in development. Some of these features are also present in the case of atmospheric resources. The question arises as to which aspects of the management of these resources can best be performed by the public sector and which ones by the private sector.

Needed Social Science Research

It is clear that many problems are emerging from man's increasing use of the atmosphere for waste disposal and from his growing capacity to modify the weather. In what ways can an expanded social science research effort help to solve some of these problems? More specifically, what kinds of social science research are most urgently required?

The problems described above have received comparatively little attention so far from social scientists, and it is clear that a considerably expanded research effort is required in this connection. Fortunately, social scientists, in examing some of these problems, will be able to draw upon work done by physical scientists, natural scientists, and engineers, and upon studies that have been undertaken by social scientists in cognate fields, particularly in the field of water resource management. The research effort to date and the types of studies that should be undertaken by various disciplines are described in detail in the appendices to this report. For present purposes, attention is confined to outlining the major types of social science research most urgently required.

Two main types of social science research are needed: studies of the relationship between the atmosphere, human activity, and biological systems; and studies of the institutional framework for the management of atmospheric resources.

Relationships Between the Atmosphere, Human Activity, and Biological Systems

It is generally recognized that weather and climate affect human activities in pervasive ways. Studies have shown that the profitability of certain economic activities depends very much on fluctuations in the weather. Other investigations have indicated that some human behavior patterns are influenced by weather variations. Still others suggest that there are important relationships between the growth and survival of certain biological species, and weather patterns. Some studies also have indicated that human activities affect weather and climate. These studies have helped to increase our understanding of the relationship of atmospheric variations to other phenomena; but much research remains to be done. Three broad categories of research are urgently required.

Weather Variations and Production Possibilities.—Research is needed to determine the influence of different weather variables on the production possibilities of various types of economic activity. Such studies would make it possible to trace the impact of a given weather change on particular industries (e.g., agriculture, manufacturing, service trades), or on a particular region. The information so derived would be useful, for example, in determining the potential impact of a given weather modification and in assessing gains and losses.

To date, most research of this type has dealt with the impact of different weather variables on agriculture. Some studies have examined effects on the construction industry, airline industry, and certain service trades, such as the retail trade. Much, however, remains to be done before the effect of a given weather variation can be traced through one industry or through the various economic activities in a given region. Studies of activities not as obviously sensitive to weather variations as agriculture or transportation are required. Means must also be found for tracing impacts of weather variations as they work their way through economic systems.

Input-output models may be very useful for studying effects of weather changes on economic systems. The model being developed for studying the economy of the Philadelphia region is an example. This model is being designed to provide information on the effects of varying degrees of water and air quality on regional economic activity. Much theoretical work has already been done in developing this model; and it is believed that models of this type can be modified to trace impacts of weather within a region, or between regions. Work on such models will benefit, of course, from empirical studies designed to determine the sensitivity of various activities to changes in different weather parameters.

A related type of study concerns the identification and measurement of a given weather change on the output potentials of a river system. River systems are managed to provide various goods and services which society requires. The effectiveness with which they are managed, however, hinges upon a knowledge of the relationships between the physical inputs (water) and the end products (goods and services). Simulation models have been developed to trace the impacts of streamflow on the operation of river basin systems. The Harvard Water Model is a case in point. This model might be made more comprehensive, so that the effects of changes in atmospheric variables on river system outputs could be studied. This would require research on the effects of varying forecasting accuracy and the length of periods on river system operating policies. In addition to such studies, research would be needed on economic loss functions associated with floods, droughts, and deficits in target outputs for hydro-electric energy, recreation, and water supply.

Weather Variations and Human Behavior.—Weather variations influence human behavior in diverse ways. Studies have shown, for example, that changes in temperature and precipitation influence productivity and the incidence of crime and illness. Much of this work, however, has related principally to particular places and particular times. As yet no theoretical models have been developed which have general application. Such models would be especially useful in studying the influence of various weather elements on crime, illness, and productivity, and in designing policies to assist adjustment to the weather. Research is also needed on the relationship of variations in weather to the use of education facilities and community services (such as fire protection, public utilities, and mass communications).

Human response to extreme weather events is another area requiring a much expanded research effort. The U.S. Weather Bureau has estimated that each year hurricanes cause property losses exceeding $250 million, and often as many as 300 lives are lost. Tornadoes are estimated to cause losses of over $200 million and more than 200 deaths each year. Floods also cause severe losses, perhaps as much as $250 million annually. Research to date suggests that there are substantial variations in human response to these extreme events: some individuals and communities seem to be much more effective in dealing with them than others.

Improved understanding of human response to extreme weather events would assist materially in developing public policies to reduce losses from such events. Particularly fruitful avenues of research would include investigations of the role of perception and attitudes both in identifying a weather event and selecting an adjustment to it, and studies of how people use weather information. Research should also be undertaken to compare communities which frequently experience such hazards with others which seldom experience them. An especially interesting study would be one designed to determine when a community develops a "disaster culture." This would require examining perceptions, attitudes and responses at various levels in the community—i.e., at the individual, family, group, organizational, and community-wide levels.

Attempts to modify the weather arouse different types of human response. In some cases such attempts are enthusiastically supported, but in others they arouse considerable opposition. Studies are needed to determine the reasons for these different responses. Specifically, such studies should include longitudinal case investigations of human responses before, during, and after specific weather changes: (1) where a modification was *planned;* (2) where no modification was actually made but people *believe* it was; and (3) where weather modification was inadvertent (e.g., air polution, or climatic changes in urbanized regions). Other longitudinal studies should examine human response to the possibility of unusual incidents, such as pollution of the atmosphere by nuclear explosion, poison gas, or other chemical means. Information from such studies would be invaluable in formulating programs and policies relating to weather modification.

Migration to avoid the effects of weather variations is another area requiring research. In some cases individuals accept the weather as given and adapt their activities accordingly. In others they try to modify the weather. In still other cases, individuals move away either temporarily or permanently to avoid the effects of weather variations. Why do some people migrate while others remain? What accounts for the resistance of some people to moving even though the occurrence of a severe weather event is imminent? Studies are needed to determine the factors underlying decisions to migrate. One type of study would focus on the migration of people and economic activities to the Sunshine Belt of the West and Southwest. Another would attempt to isolate factors which account for differential responses to warnings of floods, tornadoes and hurricanes. Still another type of study would examine factors underlying decisions to establish summer cottages in recreational areas adjacent to major metropolitan areas.

Weather Variations and Plant and Animal Communities.—Many of man's activities, including his use of atmospheric resources, have pervasive effects on natural and artificial ecosystems. Prediction of the effects of weather modification and of atmospheric pollution on natural and artificial ecosystems provides essential data for balancing the costs to society as a whole of specific human uses of the atmosphere against the benefits. The benefits are normally weighed and emphasized by proponents of new programs; but the immediate direct and indirect costs of carrying out such programs quickly become evident at the stage of operational planning. Unintended and unwanted effects on plants and animals of interest and value to man are indeed part of the cost of weather modification programs.

Some of these effects may have directly measurable costs, as when changed weather patterns trigger an outbreak of insect pests. In other cases, the effects may be mostly on those plants and animals which lack a specific monetary value, but which contribute to the quality of living for a growing segment of the public.

Ecological knowledge has not yet reached the stage where reliable predictions can be made of the probable effects of specific changes in environmental variables on plant and animal communities. Because of the inherent variability of ecological processes, it is unlikely that strictly deterministic predictions of this sort can ever be made. However, a great deal of information has been collected in the last sixty years on the relations between organisms and environment. These data have not generally been organized into predictive models useful for assessing the effects of environmental change on whole ecosystems. This now appears possible, at least in a preliminary way. The resulting models can then be used to guide additional field and laboratory research.

One useful type of research would involve reviews of currently available data on the effects of weather and climate on existing plant and animal communities. Such research would seek to establish simple hypotheses, which might then be used for further studies. Attempts should also be made to gather additional data and to develop computer models to analyze impacts of weather variations on large-scale ecosystems. An important contribution toward the provision of additional data is being made by the International Biological Program through its efforts to standardize data collection procedures and establish data banks. Studies are also underway to develop various types of models, including those based on regression, analysis of variance, and simulation.

Other studies are also required. There is a need for intensified field and laboratory investigation of the effects on specific organisms, of changes in temperature, moisture, and other environmental variables. In addition, selected natural and artificial communities should be subjected to controlled, strictly localized weather modification. It is particularly important that detailed field studies to monitor effects on plant and animal communities accompany any extensive operational tests of weather modification capabilities.

The Institutional Framework for Management of Atmospheric Resources

Another major area requiring research relates to the institutional framework for the management of atmospheric resources. The rapid increase in air pollution across the United States, the growing number of attempts to modify the weather, and the mounting toll of property damages caused by extreme weather events have led to a need for increased government intervention. Policies are required which will encourage more efficient adjustment to variations in the weather. Modifications are required in existing legal, jurisdictional, and administrative frameworks to handle the conflicts and other problems that have begun to emerge from increasing use and modification of atmospheric resources. Determining what kinds of policies and modifications of existing institutions are required, however, will depend in part on the results of some penetrating research in the social sciences.

The Process of Decisionmaking.—One area of needed research relates to the process of decisionmaking in the management, use, or modification of atmospheric resources. Studies are required to identify what decisions are made, who makes them, and what factors appear to influence the outcomes. What decisions, for example, are made about adjustment to a given weather element, such as snowfall, by individuals, private industry, and government (at various levels)? How do perceptions of snowfall and of alternative adjustments to it influence the choice of adjustment? What role does present government policy appear to play in the choice of adjustment? How do various legal, jurisdictional, and administrative frameworks influence the decision? In what ways is a choice of adjustment to snowfall related to decisions about other matters, such as the location of a factory or a home, or the purchase of an automobile?

Another useful avenue of research would be the analysis in depth of given adjustments to specific weather changes—both natural variations and planned modifications. Studies might be undertaken, for example, to identify what types of decisions are made, who makes them, and what factors appear to influence the various decisions.

The role of weather information in decisions relating to adjustment to the weather should also be examined. Who uses weather information, and in what ways? Does an increase in the amount of information or an improvement in the accuracy of weather forecasts necessarily lead to changes in production schedules or alterations in other human activities? To what extent is the meteorologist's belief in the value of increased information borne out by the manner in which people actually use the information provided? Will more accurate weather information necessarily be beneficial to everyone? For example, more accurate 8-day forecasts may lead to even greater peaks in recreational activity: facilities may thus lie idle for longer periods; and overcrowding during peak times may reduce the pleasure experienced by individuals. It is possible that some positive psychological values are associated with uncertainty about the weather. More accurate knowledge in these areas will be of great value to those designing programs of weather information, as well as to those developing policies to encourage more efficient adjustment to weather variations.

The Respective Roles of the Public and Private Sectors.—Management of atmospheric resources has been vested principally in the private sector. Recently, however, governments at various levels have begun to take increasing interest in the management of these resources. The question arises, therefore, as to which functions can most effectively be performed by each type of enterprise—by the private sector, and by the public sector.

Studies are needed to determine the extent to which existing institutional arrangements can be adapted in order to manage atmospheric resources. For example, can existing water management agencies add to their present functions the regulation and/or initiation of cloud seeding operations, and undertake the new functions efficiently? Can fire prevention districts take on lightning suppression as an additional function?

It is widely agreed that certain uses of atmospheric resources should be subjected to Federal control. Little research, however, has been done on the question of whether this function can be assumed by existing Federal agencies, or whether efficient control requires the creation of a new agency. Nor has much research been done to establish requirements for such a regulatory body, in terms of organizational structure and competence. Existing agencies should be studied to determine if their present functions can be extended to include regulation of activities involving atmospheric resources. For example, the Federal Communications Commission now does a type of geographic and atmospheric zoning in its control of radio frequencies, directional beam control, hours of operation, etc.; and the Federal Power Commission regulates various water and power systems throughout the Nation. Could these agencies effectively take on additional responsibilities for managing the use of atmospheric resources?

Studies are also needed to determine the probable effectiveness of various combinations of private, public, local, State, and Federal control in managing atmospheric resources. One type of study should consider what role is appropriate to the Federal Government. To what extent should the Federal Government, rather than governments at other levels, control human uses of the atmosphere? Various studies have urged that the Federal Government, rather than the States, should control man's use of the atmosphere, especially in regard to weather modification. While Federal control seems clearly indicated for certain modification activities (such as diverting hurricanes, modifying regional climates), such control is not so obvious for activities of smaller geographical scope and effect. Studies should be initiated to determine which weather modification activities are more appropriate for Federal and which more appropriate for State control.

A review of previous studies of government organizations concerned with water resources would be helpful in determining whether there are any parallels in the field of atmospheric resources. The organizational problems raised by the need to manage atmospheric resources appear to be similar to those raised in the water field. An assessment of how the Federal Government has handled management and organization for water resources might suggest desirable alternatives for implementing regulation in the weather modification field. Such an examination might reveal, for example, that the Federal-review board concept (as expressed in the 1949 Hoover Commission Report) and the structural framework established for Federal water projects have relevance to the problem of managing weather modification activities.

Indemnification for Damages.—Air pollution and weather modification activities raise the problem of external effects, i.e., damages to those not directly involved in the decisions to use or modify the weather. Studies are required to determine appropriate compensatory arrangements for defraying the social costs likely to be created. Various compensatory measures should be examined—for example, insurance systems, compulsory fees or user charges, local levies on property owners, and special adjudicatory arrangements. Without appropriate compensatory measures, benefits are likely to accrue only to some, while large costs are passed on unintentionally to others. The welfare of all persons affected by various uses of atmospheric resources must be safeguarded.

Innovation in Laws.—Conflicts resulting from uses of the atmosphere raise questions about the adequacy of the present legal framework to handle them. Can the court-centered, common law system deal adequately with problems caused by human uses of the atmosphere? To what extent can the present legal system be effective in such conflicts? Should administrative agencies assume some or all responsibility for handling problems raised by weather modification?

A number of factors limit the potential ability of the courts to operate effectively in this area: often, uses or modifications of the atmosphere involve very large areas and numbers of people; atmospheric changes can have subtle, albeit real, effects on particular individuals; changes in the atmosphere can pervade many aspects of life; planned modifications can result ultimately in catastrophic and irreversible effects; and finally, and possibly most important, the cause-effect relationship between altered atmosphere and damage to an individual is often impossible to prove. Studies are therefore urgently needed to assess the potential effectiveness of our present legal system in such problem areas, to consider revisions or innovations in laws, and to examine alternative mechanisms for handling conflicts.

Potential conflicts also exist between various levels of jurisdiction. Studies are needed to determine the types of mechanisms required to deal with these conflicts. Such devices as interstate compacts and international treaties and agreements should be examined for their possible value in preventing major conflicts from developing, and in providing the machinery to deal with conflicts if they do arise.

Conclusions and Recommendations

Research Required

The increasing likelihood of success in attempts to modify the weather, and the accelerating rate at which domestic and industrial wastes are contaminating the atmosphere underline the urgency of a vastly increased effort to identify the problems arising from these uses of the atmosphere and to find solutions to them. To this end, we propose an expanded program of research on the economic, social, and institutional aspects of the atmosphere as a resource. If this is done now, political, social, and legal institutions may be better prepared to deal with future crises as air pollution reaches generally unacceptable levels, and as conflicts arise among users, each seeking to manipulate the weather to his own advantage.

The Task Group makes the following specific recommendations with respect to research:

A. The National Science Foundation should take a more active role in promoting research on the social, economic, and institutional aspects of human uses of the atmosphere than it has done to date. The Foundation is well equipped to stimulate productive long-term research in this field because of its freedom from specific commitment to any single management policy or plan of action, its excellent reputation and contacts in the scientific community, and its ability to commit funds for research extending over several years. As an essential first step, the National Science Foundation should appoint an individual with a background in the social sciences to assist it in promoting research on the human dimensions of the atmosphere.

B. Operating agencies involved in research on atmospheric processes and in field tests of weather modification feasibility should be urged to devote a portion of their funds to research on the economic, social, and political implications of weather modification. Investment in efforts to learn how to manipulate atmospheric processes should be accompanied by investment in studies to identify the human consequences of such manipulation.

C. The following topics are those most urgently in need of intensified study:

1. The influence of weather parameters on industrial and biological production and on water basin supplies.
2. The influence of specific weather parameters and of extreme weather events on human behavior, activity, and response to atmospheric change.
3. The values people place on intangible or esthetic aspects of good or bad weather; and the social values they assign to plant

and animal communities likely to be altered by pollution or weather modification.

4. The consequences for management of the fact that the atmosphere is a dynamic, common property resource; and the implications of the possibility that gains from weather modification in one place may be offset by losses in another.
5. The processes of decisionmaking in the use and management of atmospheric resources.
6. The relevance of existing legal, institutional and administrative arrangements to problems of atmospheric resources; and the need for new institutional arrangements.

Specific types of studies that might be undertaken under each of these headings are noted in the body of this report and described in detail in the various appendices.

Personnel Required

There is a serious shortage of social scientists interested in the human dimensions of the atmosphere and competent to work effectively in this field. Efforts must be made now to remedy this deficiency so that research frontiers can be pushed forward and so that knowledgeable people will be available to advise those who will have to make the hard decisions in managing atmospheric resources. The Task Group therefore makes the following recommendations:

A. The National Science Foundation should sponsor programs which will encourage social scientists to cooperate with physical and biological scientists on problems related to weather. These programs should involve both mature investigators and graduate students in training. To achieve this coordination, various means are suggested:

1. Interdisciplinary research efforts extending over several years, aimed at solving a specific problem. An illustration of this type of effort is the Harvard Water Program, which has drawn together faculty members from political science, economics, and engineering who had special research interests in water resources planning and were disposed to work together in pursuit of these interests.
2. Special seminars on particular topics, which would result in a well-edited publication for wide distribution.
3. Seminars and short-term conferences with purely educational objectives, intended to stimulate interdisciplinary thinking by the participants.
4. Interdisciplinary departments of resource studies in universities.

B. The National Science Foundation and operating agencies should provide financial support for training as well as research. Support should be made available in the form of fellowships for graduate students, and grants to enable social scientists to familiarize themselves with the physical dimensions of atmospheric resources. For example, a grant might allow a social scientist to work for a period at an atmospheric research center, or to attend an atmospheric resources institute (which could be organized for this purpose).

C. The National Science Foundation and operating agencies should provide financial support to encourage social scientists working on problems in cognate fields to turn their attention to weather-related problems. For example, social scientists are working in the water resource field, in part because the problems are challenging, and in part because funds are available for them to do so. Some of these individuals might be induced to work on problems of atmospheric resources—if they were made aware of the intellectual challenge and assured adequate financial support.

Information Programs Required

Information as to how air pollution and weather modification can affect plant and animal communities of interest and value to man is essential for evaluating the social and economic costs and benefits of specific human uses of the atmosphere. Such ecological data are in general not available, and there is a serious shortage of environmental biologists able to provide the necessary data. The Task Group therefore supports the efforts being made under the auspices of the International Biological Program to accelerate the training of ecologists.

A considerable amount of information has accumulated on various aspects of human use of the atmosphere. Unfortunately, much of this information is not available in published form or in convenient locations. The Task Group therefore recommends that the National Science Foundation sponsor a program for collecting and disseminating bibliographic information and a program for cataloging relevant research efforts to date. These programs should be directed by social scientists knowledgeable in the field of atmospheric resources.

The Task Group reiterates its recommendations that all agencies engaged in research on physical processes in the atmosphere and in operational testing of weather modification procedures sponsor some research on the social, economic, and political aspects of using the atmosphere. How much support should be provided for this purpose is difficult to estimate. The mere availability of funds, of course, will not automatically produce the desired results. What is required is an accelerated program of research and training in the economic, social, institutional, and biological aspects of atmospheric resources commensurate in some degree with the expanded effort being made in the physical science aspects of weather problems.

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Appendix I

NEEDS FOR RESEARCH ON PLANNING AND DECISION-MAKING ASPECTS OF HUMAN USES OF THE ATMOSPHERE

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These summary comments are presented from the viewpoint of planning and decisionmaking rather than from the viewpoint of a specific discipline such as economics, law, or political science. Others will be presenting comments from the standpoint of specific disciplines; I feel best equipped to discuss problems of planning and decisionmaking. As will become evident, my comments are not based on detailed knowledge of the atmospheric sciences or weather modification technology and issues. Rather, they reflect information and insights gained from attendance at two meetings of the Task Group and from limited supplementary reading.

Viewed most broadly, the planning and decisionmaking questions involving use of the atmosphere as a resource should be of the same type as questions arising from the use of any other resource—water, land, or minerals. In fact, the notion of the atmosphere as a natural resource is a very powerful one: it allows one to apply the theories, methods, and insights of natural-resource planning (including water-resource planning) to the problems of human use of the atmosphere. If natural resources are viewed in terms of controllability or manageability, it is clear that the atmosphere has until recently been at the uncontrollable end of the continuum. In economic terms, its beneficial effects—rain, sunshine, clouds, and winds in the proper proportions of time, place, and intensity—have been considered free goods; its malevolent effects—floods, droughts, heat waves, and cold waves—have been considered unavoidable costs.

The theories and techniques of private and public investment economics have not been applied to the exploitation of the atmosphere as a resource, and accordingly there exists no body of empirical data on which to draw for study and analyses of planning and decisionmaking. In contrast, mineral and soil resources have been processed and managed ever since man left the forest, and there now is a body of data of man's relation to these resources from which to draw conclusions. To some extent, the problem is to obtain comparable experience and data for the atmospheric resource as soon as possible.

Considering planning and decisionmaking for atmospheric resources as analogous to that for water resources, one can think of research as concentrating on four functional relationships: the social-welfare objective function; the production or technological function; the cost-input function; and the benefit-output function. In the following sections, important questions concerning these functions, as they relate to the atmosphere, are identified.

Major Questions

1. The Social-Welfare Objective Function

Both the physical characteristics of weather and broad social and economic interdependencies dictate that objectives for atmospheric management be at least national, and in some cases international, in scope. Certainly prediction systems for tornadoes, hurricanes, flood-producing rains and ice-producing storms are based soundly on national and international objectives of saving lives and reducing injury and disease. Furthermore, weather forecasting systems which prevent or reduce economic losses have as their basis economic efficiency or maintenance of national income. Weather modification systems must also be evaluated in national terms—whether they are small-scale systems affecting only local areas, or, possibly, large-scale systems affecting much larger areas. For example, if weather modification helps area A at the expense of area B, this external effect must be taken into account in evaluating the scheme. Thus, the objective function to be used by weather managers must be established largely in national terms, even when the crises which call the weather managers to action appear to be of local or regional scope.

The relevant questions to be asked are:

A. What form should the objective function for atmospheric management take? What are its elements: public health, safety, economic efficiency?

B. How should the objective function be developed? Who should develop it: an administrative agency, the President, the Congress?

C. How can a national objective function be enforced, given the inherently local nature of most weather crises and the tendency of localities and regions to take actions based on their own narrow objectives?

D. To what extent is national regulation of weather modification activities necessary in order that national objectives be attained? Can State or local regulation be satisfactory?

E. What kinds of information on the nature of weather phenomena and spillover effects of local weather modification are required to answer the above?

Apparently, little research has been undertaken or is now under way on the problems of relating objectives to atmospheric management. The Harvard Water Program has carried on general research on the complex objective function (Maass et al., 1962; see also Maass, 1966). Urban planners have written extensively on multiple goal formulation; and operations research and systems analysis specialists have fully developed the notion of maximizing the value of the objective function.

This entire conceptual apparatus can be applied with little modification to problems of atmospheric management. But the basic work of applying the objective function to the atmospheric field remains to be done. Perhaps the first research on applications will come from those working on air pollution. For example, a recent article (Kneese, 1966) draws the parallel between water and air pollution and provides some insights into applications problems. Further elaboration is contained in my article "Environmental Planning with Special Relation to Natural Resources" (in a report on environmental planning, edited by John Dyckman, of the University of California, publication forthcoming).

2. The Production or Technological Function

Some of the most intractable questions relating to atmospheric management concern the relationships of inputs (for weather modification and weather forecasting) to physical outputs. What are the physical results in the form of increased rainfall, for example) of applying weather modification measures (seeding clouds with silver iodide, for example)? How can these results be measured? Can they be duplicated, or is each application unique? How accurate have rain and runoff forecasts been? Do affected individuals make good use of the forecasts, or are there behavioral and institutional factors which work against effective use of forecasts?

One could hold that until we have adequate, detailed information on production-function relationships, much social and economic research is premature—since it must be based largely on analogy from other production functions rather than on data from management of the atmospheric resource. At first glance, research on the production or technological function would appear to be a task solely for natural scientists (NCAR, ESSA, and university and research institute scientists). But if such research is to be meaningful for planning and decisionmaking, social scientists must participate in setting up the experiments and conducting the research.

For example, an experiment on the effectiveness of cloud seeding might be designed so that at least one precipitation-measurement station is located in each minor political or management jurisdiction—township, watershed district, city or town; and that scientific measurement of precipitation be accompanied by measurements (using survey research techniques) of people's perceptions of precipitation. Also, studies of the accuracy of rainfall, snowfall, or streamflow predictions can be accompanied by behavioral research on the responses of individuals and institutions to predictions. For example, is degree of response highly correlated with degree of accuracy of prediction?

Others will report in some detail on production-function research under way on weather modification and weather forecasting. Certainly, much of the Bureau of Reclamation's work on weather modification is of this type; and private meteorologists collect information on the results of their attempts to modify the weather. Research on weather description and prediction is well-established at NCAR and ESSA.

It appears, however, that very little production-function research has any social science component. Certainly this was the finding in 1964 of the Weather Bureau study *The National Research Effort on Improved Weather Description and Prediction for Social and Economic Purposes.* In that study, "systems" research and "synthesis" research (which deal with the social and economic impact of weather management) were found to be extremely inadequate.

3. The Cost-Input Function

Cost-input functions are the capital costs and the operation, maintenance and replacement (OMR) costs which go into weather modification and prediction programs. Data on these functions are obtained from natural science and technological research, and from testing new methods and techniques. The economic feasibility of specific weather management techniques is influenced greatly by these cost considerations.

In general—and quite in contrast to probems of benefit estimation—the problems of estimating capital and OMR costs of resource inputs to weather management measures are not great. Once the production function is known, and given the capacity of industry and government to develop and maintain the necessary facilities and equipment, costing of resource inputs is manageable. The term "costs" as used here does not include adverse external effects, which are costs in another sense. These may indeed be difficult to measure; they are considered under the "Benefit-Output Function" section of this paper.

There are interesting and significant research problems associated with cost estimation, especially where uncertainty is present in high degree. Costing of research and development (R. & D.) projects is particularly uncertain, and this would appear to be especially true for large-scale weather measurement and modification schemes. Research on atmospheric cost-input functions should take into account the results and experience derived from analogous R. & D. programs in the defense and aerospace industries.

4. The Benefit-Output Function

The benefit-output function, like the objective function, is central to research on atmospheric management. A whole set of specific questions derives from the general question of the value to man and society of particular atmospheric management measures—weather forecasting or control.

According to one view of public investment theory, benefits are defined as positive contributions to the attainment of an objective. Thus, where the objective is economic efficiency, benefits are in terms of economic efficiency (or, as a surrogate, national income). Where the objective is public safety, benefits are measured in terms of lives saved or injuries averted. These may be converted to national income terms, if one chooses to make some heroic assumptions on the value of human life, but this is not essential to using such life and accident data.

It seems sensible, therefore, to develop a set of research questions organized on the following basis:

A. What are likely to be the major objectives of atmospheric management by government?

B. For each objective, what are the specific elements with which we can measure attainment of the objective?

C. In what units are such elements to be measured?

D. What are the conceptual and empirical problems of measuring contributions toward the objective?

Specific subquestions to questions *B*, *C*, and *D* are likely to be quite different for the economic efficiency objective than for the public health and safety objective. For economic efficiency, research questions and methodology are likely to be quite different where the response of decision-makers can be assumed to be rational, than where this cannot realistically be assumed. For example, when flood forecasting is followed by efforts of industrial and business firms to take preventive action, forecasting benefits can safely be assumed. But where reactions of individuals to such information are unknown or are found to be "irrational," benefit estimation is likely to be difficult. In these instances, behavioral research is indicated.

For the public health and safety objective, estimates in terms of lives saved and injuries prevented must necessarily be expressed in probabilistic terms; and they are dependent to some degree on behavioral assumptions. In most cases, strong public action to evacuate flood-menaced areas, or to take shelter from tornadoes or hurricanes, can be assumed. But there is also likely to be a strong random element at work in human reactions to atmospheric phenomena, and to weather forecasting and control. Benefits will always have a substantial element of uncertainty.

Systems Research

The social and economic effects of atmospheric management can be thought of as outputs of a physical-technologic-socio-economic system. For example, weather modification will change rainfall inputs to a given hydrologic system, which may or may not be controlled or disturbed by works of man. Using systems analysis—simulation, for example—rainfall effects can be traced through a water-resource system to outputs in the form of water supplies of particular quality delivered to points of use according to a specific time schedule—or in the forms of controlled high and low flows, electric energy produced, and recreation services provided.

Simulation techniques have been developed and are now in use for tracing the effects of natural or controlled streamflows through hydrologic systems. As a contribution to the work of this Task Group, we are currently investigating problems of tracing the effects of rainfall and rainfall modification on such systems via simulation.

An important area of research involves the estimation of benefits or values to be derived by people from these physical effects. Such research must be directed specifically toward estimating values in a particular systems context, or for outputs or consequences with specific temporal and spatial characteristics.

As an example, economic losses from shortages of irrigation water (or benefits gained by averting such shortages) are functions of the water user's expectations, his strategy for using water, and his degree or extent of advance knowledge of shortages or the availability of extra water. Also, unit economic losses are affected by the existence of prior economic losses—which can be analyzed by serial correlation.

An approach to such research would be the selection of typical water management operations—an irrigation system in the West, a hydro-power system, a river regulating system such as on the upper Wisconsin River—as case areas to be studied intensively to determine as precisely as possible the values obtained from the water control systems under different patterns and circumstances of operation.

An important element of such research would be behavioral studies where the actions and attitudes of individual farmers, homeowners, and businessmen are the relevant determinants of values derived from water-resource products and services.

Major research is necessary to adapt existing river system simulation models for use in testing the physical and economic effects of atmospheric management. Further details are presented in a separate report by Myron Fiering, Jabbar Sherwani, and this author. Following is a summary of the major research required in this area.

A. *Generation of synthetic precipitation records for input to simulation models.*—Development of models for synthesis of precipitation is still in its early stage. There has been little application of synthetic precipitation sequences as inputs to water resource simulation models. Work on synthetic precipitation models must be extended to make them suitable for use in water-resource system simulation.

B. *Expansion of Stanford-type (Crawford-Linsley) precipitation-runoff models to other kinds of river systems and hydrologies.*—This precipitation-runoff model performs the function of producing runoff consequences from various precipitation patterns. The model has been applied to several types of watersheds. Further research is needed to generalize this type of model for use in a wide range of watersheds, and to extend applicability of the model to the full range of rainfall records available, including daily and monthly records. Also, research and experimentation are required to determine if the Stanford-type model can be used effectively in conjunction with a river system simulation model of the Lehigh basin type, developed by the Harvard Water Program (Hufschmidt and Fiering, 1966).

C. *Amplification and testing of the Fiering multi-lag correlogram model, using precipitation data as well as runoff data.*—This model uses the statistical characteristics of both runoff and precipitation events to account for discrepancies noted in flow correlograms. Resolution is obtained by including the effects on current flows of the flows of a number of earlier periods (instead of only the previous period, as in a simple Markov model). The goal here is to develop the equivalence of a generating model (based on the statistical parameters of both rainfall and runoff) to that of a model based on several antecedent flow events. Thus, when rainfall modification is assumed, the statistical parameters of the rainfall can be changed accordingly, and the model will then yield the synthetic sequences of runoff which are appropriate for the modified precipitation.

D. *Research on testing the applicability of reservoir release allocation rules under various assumptions of rainfall and runoff forecasting.*—(The Space Rule developed by the Harvard Water Program, and reported in Hufschmidt and Fiering, "Simulation Techniques," is an example.) Perfect allocations can be achieved only with perfect foreknowledge, which is, of course, unattainable. As rainfall and runoff forecasting improves in reliability, allocation rules become more effective, if the rules are appropriate to the degree of reliability of the forecasts. Further research is required in these areas.

E. *Research on the utility of hedging rules for complex systems.*—For the single-reservoir, single-purpose case, hedging rules contribute little to improving net benefits for a wide range of economic loss functions (Young, 1966). Hedging becomes more meaningful in operating a system when forecasting is more reliable. Further research is needed on the utility of hedging for multiunit, multipurpose systems, under various assumed degrees of forecasting reliability, along the lines of research currently being carried on by Fiering.

F. *Research on economic loss functions under various assumed conditions.*—Further study is needed on economic loss functions associated with floods, droughts, deficits in target outputs for energy, recreation, and water supply. In particular, there is need to investigate the nature of such functions under various assumed conditions: with and without weather modification and forecasting. Finally, the behavioral relations and actions of farmers, industrial concerns, and householders have to be investigated to determine how such groups react to various water management measures.

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Appendix II

CONTRIBUTIONS OF GEOGRAPHICAL ANALYSIS TO THE STUDY OF HUMAN RESPONSE TO WEATHER AND CLIMATE

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Perhaps the most famous remark about the weather is one attributed to Mark Twain: "Everybody talks about the weather but nobody does anything about it." [1] Despite its obvious wit, the remark is not a completely fair reflection of the facts. While it is true that the weather probably provides one of the world's most popular topics of conversation, it is not true to say that nobody does anything about it. On the contrary, considerable human energy is devoted to accommodating weather and climate.

Traditionally, weather and climate have aroused three main types of human response: adaptation, adjustment, and movement.[2] Men adapt physiologically to wide ranges of temperature, precipitation, and wind. For many kinds of human activity, weather and climate have little or no perceptible effect on the type of activity pursued or the rhythm of its pursuit, and so no response is required. Some activities, however, are affected in important ways by variations in atmospheric conditions; and men try to adjust to these changes in various ways. They may permanently insulate themselves from the effects of weather, as in constructing storm-proof buildings or developing drought-resistant crops; or they may temporarily offset the effects by wearing appropriate clothing or rescheduling an activity, as in delaying a harvest or postponing a vacation trip.

Another type of response is movement. In some cases man finds he is unable physically or psychologically to withstand severe climatic conditions, such as long periods of cold or hot weather, or persistent rain. Technology, while it may help adjustment to such conditions, may be too costly, or may result in an environment so artificial that it is abandoned. Movement, then, may be a permanent or temporary response to harsh climatic conditions. There is a considerable amount of temporary movement, for example, in response to severe weather events, or to extreme winters or hot humid summers.

Until recently, man's response to weather and climate has been concentrated mainly on adaptation, adjustment, and movement. It is true that weather modification attempts have been made almost since the dawn of civilization to increase or reduce rainfall, suppress lightning, and disperse hailstorms. However, lack of proof of the success of these attempts has resulted in weather modification being regarded by most people as an interesting idea but impossible to achieve on a consistent basis. Most skeptical of all have been research scientists studying the atmosphere.[3]

In the past few years, however, views about the possibilities of modifying the weather have changed. In 1957, for example, the conclusion of the President's Advisory Committee on Weather Control that substantial increases in precipitation could be achieved by artificial means was regarded with much skepticism by professional meteorologists.[4] In 1966, however, similar findings of the Special Commission on Weather Modification [5] and the National Academy of Sciences-National Research Council Committee on Weather and Climate Modification [6] aroused comparatively little debate among scientists. These two groups also concluded that cold fog can be dispersed and lightning suppressed, and that prospects for suppressing hail are bright.

Man's increasing ability to modify the weather raises possibilities of reducing weather-caused losses on the one hand, and increasing the production of certain goods and services on the other. Losses from major storms, lightning, and floods continue to mount. It has been suggestsd that such losses may be reduced by altering the physical processes that produce them. Airlines, for examplee, can no doubt cut their losses and expand their activities if it becomes possible to provide suitable flying conditions at required times. It may also be possible to control precipitation, sunshine, and temperature in ways that will increase agricultural production substantially, and thus help solve the world's food problem. Many other advantages may be visualized and claimed for weather modification.

Weather modification alters the weather for everyone. Not everyone, however, wants the weather changed in the same way, or to the same degree. Increased precipitation may benefit a hydro-electric power company by augmenting the water supply in its reservoirs and thus increasing its revenues; but precipitation induced for this purpose may ruin vacations for tourists in the reservoir area. Some farmers may benefit from an extra two inches of rain; but others may suffer severe losses from additional precipitation. Not only may weather modification have differential effects within a given area but it may also create differential effects in several other areas. One area may benefit by an increase in precipitation; but this increase may reduce precipitation in neighboring areas.[7] Decisions about weather modification, therefore, need to take into account overall gains and losses.

Parallel to the new opportunities for weather modification are improvements in the range and quality of forecasts. The advent of satellites, the World Weather Watch, and the improved numerical models of the atmosphere linked to bigger and faster computers suggests that, for example, 8-day forecasts with good accuracy for the 8th day are only a decade away.

Weather modification and improved information systems widen the range of alternatives from which one can choose an accommmodation to weather and climate. Which alternative is superior in a given instance depends on a careful weighing of the overall gain- and loss-probabilities of the various alternatives—adaptation, adjustment, movement, and modification. The following questions give some indication of what it would be desirable to know to permit an objective appraisal of various alternatives:

A. To what extent are various human activities sensitive to changes in the weather?

B. What is the impact of weather and climate on choice of location (e.g., for industry)?

C. How does weather affect the decision-making process?

D. How do human activities affect the weather?

Geographers have made a number of useful contributions to the study of these questions. Gaps, however, exist, and these need to be filled before completely satisfactory answers can be given. The types of studies that have been undertaken to date, and those to which priority should now be given are summarized in the following sections.

Contributions to Geographical Literature [8]

From an early stage in the development of their discipline, geographers have been interested in the relationships between human activity and climatic variations. At times, this relationship was believed to be so important that attempts were made to explain the distribution of population and economic activities almost entirely in terms of climatic conditions.[9] Environmental determinism eventually gave way to "probabilism" and "possibilism"; but the belief that climate does exert a profound influence on human activity still has close adherents.[10] A considerable portion of geographical literature assumes this relationship.

Geographical analysis has been concerned with the physical aspects of weather and climate on the one hand, and with human response to weather and climate on the other. Several important contributions have been made in the development of climatological theory, and in the classification of climates. The work of C. W. Thornthwaite and his associates in particular has provided the theory and classification prerequisite to evaluating the human use of the atmosphere.[11] Contributions relating to human dimensions of the problem have been concerned with analyzing impacts of weather and climate on various types of economic activity, and studying physiological effects of atmospheric variables on human beings, animals, and plants.

Effects of Weather and Climate on Agriculture

The fortunes of some economic activities are closely related to fluctuations in the weather. Such is the case with agriculture. Although technological advances have made possible the development of weather-resistant crops, and improvements in weather forecasting have permitted minor adjustments in planting and harvesting schedules, agricultural production in many parts of the world is still very much at the mercy of the weather.

Numerous geographical studies have provided information about agriculture and the weather in different parts of the world. Some of these studies have analyzed the relationship between rainfall and crop yield,[12] and others have determined effects of particular weather events on agriculture.[13] The focus of geographical inquiry, however, is now changing from description to analysis, and to the development of theories about the relationships between climatic variations and agricultural production. For example, in Maunder's study of the implications of climatic variations in New Zealand, a model is developed for determining the overall impact of variations in different weather parameters on the economy of a region.[14] Curry's work in analyzing the seasonal programming of agriculture [15] is also indicative of the change in focus.

Effects of Weather and Climate on Manufacturing Industry

Considerable geographical research, especially in recent years, has been concerned with the location of manufacturing industry. Valuable studies have examined specific industries and manufacturing activity in particular regions. In addition, geographers have made major contributions to understanding the distribution of such activity by developing and applying theoretical models.

In trying to explain the selection of location for manufacturing industry, geographers have examined the potential importance of a wide variety of factors, including climate. Most researchers seem to have concluded that climate and weather are seldom major determinants of location, and that they generally do not substantially affect manufacturing operations. Summarizing the findings of a series of monographs on applied meteorology (published in 1957), J. A. Russell noted that climate and weather appeared to influence only the construction, automotive, and aircraft industries to any major degree.[16] Other industries, suggested Russell, were either unaffected by variations in precipitation, temperature, pressure or wind, or they had been able to protect themselves against weather effects at insignificant cost. Valuable as these studies have been for isolating the possible effects of various weather parameters on different industrial processes, they have failed to provide information on the economic significance of these effects.

In an indirect way, climate may have some influence on industrial location. The migration of population to the West since the second World War reflects the fact that technological advances and growing affluence have loosened locational ties. The list of "footloose" industries has grown enormously in the past twenty years. Arizona, California, Texas, and Florida have become magnets for population and for many industries.[17] Recognition of these forces led to E. L. Ullman's pioneering study of the role of amenities in industrial location. Unfortunately, in later geographical studies, the amenities factor seems to have received relatively little attention.

Effects of Weather and Climate on Activities Other Than Economic Activities

Studies by natural scientists and others have shown that human activities are affected in a wide variety of ways by changes in the weather. Human beings are able to withstand considerable extremes of temperature, but productivity seems to fall rapidly before these extremes are reached. Productivity also varies with fluctuations in rainfall, wind, and pressure; and such changes seem to stimulate various psychological reactions as well.[19]

A variety of geographical studies have examined physiological and psychological reactions to fluctuations in the weather. Maunder has attempted a classification of climate based on indices of human comfort.[20] More recently, Terjung has devised comfort and wind effect indices to produce a map of annual physioclimatic extremes in the United States.[21] Lee and Lemons have studied man's adaptation to climate as revealed by his adoption of different types of clothing.[22] Several geographers have studied geographical aspects of public health. Shosin, for example, has examined the incidence of various types of disease in the Soviet Union.[23] Murray has investigated causes of death in England and Wales as they relate to the weather.[24] Lee has also examined the problems the armed forces face in adapting to foreign climates.[25] Studies by applied climatologists of impacts of weather on human physiology, psychology and activity have complemented research undertaken by geographers.[26]

Climate, Weather, and the Decision-Making Process

Man's accommodation of his atmospheric environment no doubt reflects his perception of the effects of temperature, precipitation, and wind, and his perception of the opportunities for adapting to them. The fact that he rejects some climatic regions and accepts others indicates that he finds it difficult or impossible to pursue certain activities where temperatures are very high or very low, where precipitation is too sparse or too heavy, or where winds are especially strong. Whether or not he rejects these types of climate, or how he accommodates to them, varies considerably from region to region, and reflects differing cultural backgrounds, levels of technology, levels of economic development, and so on.

A few studies by geographers have furthered understanding of the influence of perception and attitudes on human adjustment to the atmosphere. A study by Kates of perception of flood hazards [27] and research by Burton and Kates [28] on other natural hazards have provided a framework for analyzing human adjustment to variable physical phenomena, such as floods and winds. Saarinen's examination of adjustment to drought in the Great Plains [29] and Rooney's investigation of adjustment to snow in various parts of the United States [30] have furnished additional insights into the relationship between perception of weather events and human adjustments to them.[31] In another vein, studies by Saarinen [32] and by Sewell and Day [33] of the relationships between perception of the effectiveness of weather modification and attitudes toward its adoption have suggested new avenues of inquiry into man's accommodation of weather variations. A relatively new technique of analysis—the Theory of Games—has been introduced by Gould as a research tool and conceptual framework for studying human and economic geography.[34] The study of the role of perception and attitudes in decisionmaking related to the use of atmospheric resources, however, remains a critically important, but still relatively undeveloped area of inquiry.

Effects of Human Activities on Weather and Climate

The physical environment places various limitations on human settlement and activity. But man himself also creates limitations in his attempts to accommodate environment. Hence, in many parts of the world, concern about the effects of human activity on land, water, and the atmosphere is growing.

Geographers have tried to trace the impact of certain human activities on the physical environment. Some have studied the effects of deforestation on portions of the hydrologic cycle,[35] and the effects of human activities on weather and climate, for example, in connection with the formation of deserts.[36] A few have shown particular concern with the effects of human activity on the atmosphere.[37] Others have investigated the effects of urbanization on climate,[38] and the influence of urbanization and industrialization on pollution and the weather.[39]

Purposeful Weather Modification

As noted earlier, man can either adapt to the weather, adjust his activities to accommodate it, or try to alter the processes which produce it. Although geographers have shown considerable interest in other forms of human modification of the physical environment (such as agricultural development, harnessing of water resources, and deforestation), they have undertaken only a few studies of weather modification. Apart from contributions by Ackerman[40] and Spilhaus,[41] little in the geographical literature has dealt specifically with this subject.

Geographers, like other social scientists, have had little incentive to examine weather modification as an alternative means of coping with the physical environment. Uncertainty as to the possibilities of altering the weather, and lack of funds for research relating to weather modification have confined their efforts to studying other human responses to weather and climate. However, several geographers, who participated in the recent Symposium on the Economic and Social Effects of Weather Modification, have since become involved in research relating to weather modification. The present commitment of geographers to this field of inquiry remains extremely small, a situation that is unlikely to change unless major efforts are made to emphasize the importance of research in this area, and unless adequate funds are made available for the required training and research.

Priorities for Future Research

Some questions relating to human adjustment to weather and climate have been identified; and past contributions to geographical literature on these matters have been reviewed. Now, the issue is to outline directions which future research on human adjustment to the atmosphere should take. Four main lines of inquiry are recommended, corresponding to the four major questions posed earlier in the paper. Some of this research can usefully be undertaken by geographers, and some of it by workers from other disciplines.

Sensitivity of Activities to Weather and Climate

Human activities differ considerably in their sensitivity to temperature, precipitation, and wind. While some activities can be undertaken under a wide range of atmospheric conditions, others are profoundly affected by the slightest change in weather. Our knowledge of these sensitivities, however, is imprecise and incomplete. Information about agricultural impacts is much more comprehensive than that regarding most other activities, but it is still incomplete. Data on the effects of weather variations on manufacturing industry are almost non-existent. Apart from a few studies of effects on the transportation industry,[42] construction industry,[43] and some tertiary industries,[44] impacts on non-agricultural industries have been investigated only to a minor extent. Much more work needs to be done before precise estimates of effects of changes in various weather parameters on given industries or activities can be developed, and before the impact of such changes on the economy as a whole can be traced.[45]

Two broad types of investigation are needed: studies of impacts on particular industries, and studies of effects on different regions. Their ultimate purpose should be to make possible answers to such questions as the following: what is the economic and/or social significance of an extra inch of rainfall or an extra degree of temperature for a particular activity? What is the economic impact of hailstorms or hurricanes on given regions?

Models capable of giving preliminary answers to these questions are presently available. The use of input-output analysis for both intra-regional and inter-regional evaluation of weather modification and information programs has been proposed by Langford.[46] Such models trace through a regional economic system the alterations in production functions that follow from weather modification or from improvements in information systems. Potentially these models can take into account the inter-regional effects as well.

Simulation of climatological events has been proposed by McQuigg[47] and Fiering,[48] in order to examine trade-offs between assumed levels of information and modification potential. For example, using the methodology developed by the Harvard Water Program,[49] it should be possible to examine the countervailing effects of hurricane modification. Hurricane modification, for example, can provide very positive benefits by preventing property damage and loss of life from floods and winds. At the same time, such modification can produce negative benefits by reducing regional water supplies. Important questions are raised as a result. What is the incremental contribution of hurricane-derived moisture to water supplies in the Northeast, in the Southwest? If all hurricanes were to be dissipated at sea, would New York's water supply problems be further aggravated? To what extent? Answers to such questions would help in assessing not only the immediate effects but also the long-term results of specific weather modification efforts and the desirability of implementing such programs.

Impact of Weather and Climate on Locational Decisions

As noted earlier, although climate has usually not been a major factor in locational decisions, its importance seems to have grown. The desire to live in a pleasant climate, combined with increasing labor and industrial mobility, has contributed to the growth of the Far West, Southwest, and Southeast.

Although it is clear that climate has played a role in the development of these regions, it is not certain how significant this factor has been when compared with others. How important a role increased labor mobility and increased industrial mobility have played is not clear. In some cases, industries have moved in to take advantage of growing pools of labor. In others, industrial concerns located in regions of pleasant climate have conducted nationwide campaigns to attract workers to their plants. In still other cases, industries have been attracted into such areas to serve the needs of retirement populations.

Studies are needed to determine the influence of climate in the postwar expansion of the West, Southwest, and Southeast. Research should be undertaken, for example, to examine the reasons why people have moved to Tucson, Ariz., or Santa Barbara, Calif. Studies of the requirements of industries which have moved into such regions should also be valuable. Much needs to be added to Ullman's thoughts on the role of amenities in regional growth.

Role of Weather and Climate in Decisionmaking

How do people decide which of several alternative means of accommodating different weather parameters is the most appropriate? Much depends upon how they perceive these parameters, and on their perception of and attitudes towards various alternative adjustments to temperature, precipitation, and wind. Relatively little is known, however, about such perceptions and attitudes. For example, what factors condition the manner in which people interpret and respond to information given in a weather forecast? Why do some people welcome weather modification activity but others oppose it?

Despite our present inability to specify, for example, how weather information is in fact used, some progress has been made in developing normative models to describe how information or weather modification can be used. A number of examples have been prepared dealing with the demand for natural gas and with the scheduling of agricultural and other activities.[50] Further work can usefully be undertaken in this connection. In addition, a much more vigorous effort needs to be made to improve understanding of perceptions of and attitudes toward various types of adjustment to the weather.

Effects of Human Activities on Weather and Climate

In addition to studies of human response to the atmospheric environment, investigations are also needed to improve knowledge of the effects of human activity on the atmosphere. As noted earlier, a few studies have examined the influence of urbanization on climate and weather. Some have indicated, for example, that cities may provide radically different radiation regimes than less populated areas.[51] Within a city, the varied man-made topography seems to result in changes in wind patterns and temperature. On a larger scale, regional climates may be altered, for example, by man-made lakes.[52] In a more speculative realm, some studies suggest that the earth is heating up from the increased CO_2 content of the air;[53] that the formation of deserts is related to dust particles in the atmosphere;[54] and that jet contrails of future supersonic planes may be a potential source of climatic disturbance. It is possible that inadvertent modification of the weather will become even more important than purposeful modification as a problem demanding social action. Studies in this connection, therefore, appear to be especially urgent.

Conclusion

The foregoing suggestions for studies are intended to illustrate the types of problems that merit attention. Many other topics can, of course, be proposed. At this juncture, however, it seems that the types of studies recommended are of particular concern and require early attention. Studies are urgently needed to examine sensitivities of human activities to weather and climate; to determine the impact of weather and climate on locational decisions; to investigate the role of weather and climate in decisionmaking; and to determine the effects of human activities on weather and climate.

FOOTNOTES

1. Commonly ascribed to S. L. Clemens (Mark Twain) although never appearing in his written works, H. L. Mencken, in *A New Dictionary of Quotations on Historical Principles*, Knopf, New York, 1942, p. 1278.
2. J. Sonnenfeld in "Variable Values in Space and Landscape: An Inquiry into the Nature of Environmental Necessity," *The Journal of Social Issues*, vol. 22, No. 4, 1966, pp. 71–82 describes two major sets of reactions to the physical environment: adjustment and adaptation. In his interpretation, movement and modification are presumably part of adjustment.
3. See Horace Byers, "What Are We Doing About the Weather?" in Henry Jarrett, ed., *Science and Resources*, Johns Hopkins Press, Baltimore, Md., 1959, pp. 37–53.
4. U.S. Advisory Committee on Weather Control, *Final Report*, Washington, D.C., 1957.
5. National Science Foundation, Special Commission on Weather Modification, *Weather and Climate Modification*, Washington, D.C., 1966.
6. National Academy of Sciences-National Research Council, *Weather and Climate Modification*, 2 vols., Washington, D.C., 1966.

7. Some uncertainty exists as to whether increases of precipitation in one region can only be achieved at the expense of reductions in precipitation elsewhere. Evidence from research connected with the University of Chicago project "Whitetop" raises the possibility that such decreases may occur in the wake of increases.
8. This review is based mainly on a search through geographical journals and periodicals in the English language. It also covers contributions to various meteorological and geophysical journals, and a number of publications in the natural and social sciences.
9. See, for example, Ellsworth Huntington, *Civilization and Climate*, Yale University Press, New Haven, Conn., 1915; *Principles of Human Geography*, John Wiley and Sons, Inc., New York, N.Y., 1922; and *Mainsprings of Civilization*, John Wiley and Sons, Inc., New York, N.Y., 1945. For a recent review, see Gordon R. Lewthwaite, "Environmentalism and Determinism: A Search for Clarification," *Annals of the Association of American Geographers*, vol. 56, No. 1, March 1966, pp. 1–23.
10. See Erhard Rostlund, "Twentieth-Century Magic," in P. L. Wagner and M. W. Mikesell, eds., *Readings in Cultural Geography*, University of Chicago Press, Chicago, Ill., 1962, pp. 48–53.
11. See, for example, C. W. Thornthwaite, "The Climates of North America According to a New Classification," *Geograpical Review*, vol. 21, 1931, pp. 633–655; "An Approach toward a Rational Classification of Climate," *Geographical Review*, vol. 38, 1948, pp. 55–94; and "Problems in the Classification of Climates," *Geographical Review*, vol. 33, 1943, pp. 658–659.
12. See, for example, P. N. Hore, "Rainfall, Rice Yields and Irrigation Needs in West Bengali," *Geography*, vol. 49, No. 2, 1964, pp. 114–121; T. F. Barton, "Rainfall and Rice in Thailand," *Journal of Geography*, vol. 42, No. 9, 1963, pp. 414–419; S. A. Visher, "Weather Influences and Crop Yields," *Annals of the Association of American Geographers*, vol. 16, No. 4, 1940, pp. 437–443.
13. See, for example, W. C. Calef, "The Winter of 1948–49 in the Great Plains," *Annals of the Association of American Geographers*, vol. 40, 1950, pp. 267–292; U. P. Subrahmanyam and A. R. Subrahmanyam, "A Climate Study of Drought in Peninsular India," *Geographical Journal*, vol. 129, No. 1, 1963, pp. 122–125; and L. Hewes, "Causes of Wheat Failure in the Dry Farming Region, Central Great Plains," *Economic Geography*, vol. 41, No. 4, 1965, pp. 313–330.
14. W. J. Maunder, "Climate Variations in Agricultural Production in New Zealand," *New Zealand Geographer*, vol. 22, No. 1, 1966, pp. 55–69.
15. Leslie Curry, "Climate and Economic Life: A New Approach with Examples from the U.S.A.," *Geographical Review*, vol. 42, 1952, pp. 367–383; and "The Climatic Resources of Intensive Grassland Farming: The Waikato, New Zealand." *Geographical Review*, vol. 52, 1962, pp. 174–194.
16. J. A. Russell, "The Problem, Method and Conclusions: Industrial Operations Under Extremes of Weather," *Meteorological Monographs*, vol. 2, No. 9. American Meteorological Society, May 1957, pp. 1–9.
17. A few studies have dealt with the growth of urban communities in areas of pleasant climate: Margaret T. Parker, "Tucson, City of Sunshine," *Economic Geography*, vol. 24, No. 2, 1948, pp. 79–113; and Andrew Wilson, "The Impact of Climate on Industrial Growth: Tucson, Arizona—a Case Study," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification*, University of Chicago, Department of Geography Research Series No. 105, Chicago, Ill., 1965, pp. 249–260.
18. Edward L. Ullman, "Amenities as a Factor in Regional Growth," *Geographical Review*, vol. 44, 1954, pp. 119–132.
19. For a review of the literature dealing with the effects of climate and weather on

human beings, see Marston Bates, "The Role of Weather in Human Behaviour," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification, op. cit.*, pp. 393–407; and S. W. Tromp, *Medical Biometeorology*, Elsevier Publishing Co., Amsterdam, London, and New York, 1963.
20. W. J. Maunder, "A Human Classification of Climates," *Weather*, vol. 17, 1962, pp. 3–12.
21. Werner H. Terjung, "Physiologic Climates of the Conterminous United States," *Annals of the Association of American Geographers*, vol. 56, No. 1, March 1966, pp. 141–179; and "Annal Physioclimatic Stresses and Regimes in the United States," *Geographical Review*, vol. 57, No. 2, April 1967, pp. 225–240.
22. D. H. K. Lee and H. Lemons, "Clothing for Global Man," *Geographical Review*, vol. 39, 1949, pp. 181–213.
23. A. A. Shosin, "Geographical Aspects of Public Health," *Soviet Geography*, vol. 5, No. 7, 1964, pp. 68–72.
24. H. Murray, "The Geography of Death in England and Wales," *Annals of the Association of American Geographers*, vol. 52, 1962, pp. 130–139.
25. D. H. K. Lee, "The Role of Bioclimatology in the Armed Forces," *Bulletin of the American Meteorological Society*, vol. 41, 1960, pp. 235–237.
26. Studies by applied climatologists of impacts of weather variations on human physiology, psychology and activity include: R. L. Hendrick, "An Outdoor Weather Comfort Index for the Summer Season in Hartford, Connecticut," *Bulletin of the American Meteorological Society*, vol. 40, 1959, pp. 620–623; B. M. Stephenson, "An Index of Comfort for Singapore," *Meteorology Magazine*, vol. 92, 1963, pp. 338–345; F. Fergusson, "Summer Weather at English Seaside," *Weather*, vol. 19, No. 5, 1964, pp. 144–146; C. A. Hill, "Weather and Health," *New Scientist*, vol. 4, 1958, pp. 1583–84; C. A. Mills, "Depression Weather and Health," *Human Biology*, vol. 10, No. 3, 1938, pp. 388–399; C. A. Mills, "The Influence of Climate and Geography on Health," *Bulletin of the New York Academy of Medicine*, Series II, vol. 17, No. 12, 1941, pp. 922–933; A. C. Burton and O. G. Edholm, *Man in a Cold Environment: Physiological and Pathological Effects of Exposure to Low Temperature*, London, England, 1955; W. S. S. Ladell, "The Influence of Environment in Arid Regions on the Biology of Man (the Physiological Approach to Climate)," UNESCO Arid Zone Research VIII, *Human and Animal Ecological Reviews of Research*, 1957, pp. 43–99; UNESCO Arid Zone Research, *Environmental Physiology and Psychology in Arid Conditions*, 1963; and UNESCO Arid Zone Research, *Symposium on Physiology and Psychology in Arid and Semi-Arid Conditions*, 1964. The major reference source for the effects of weather and climate on physiology and psychology is S. W. Tromp, *Medical Biometeorology, op. cit.*
27. R. W. Kates, *Hazard and Choice Perception in Flood Plain Management*, University of Chicago, Department of Geography Research Series No. 78, Chicago, Ill., 1962.
28. See, for example, Ian Burton and R. W. Kates, "The Flood Plain and the Sea Shore: A Comparative Analysis of Hazard Zone Occupance," *Geographical Review*, vol. 54, July 1964, pp. 366–385.
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30. J. F. Rooney, Jr., "The Urban Snow Hazard: An Analysis of the Disruptive Impact of Snowfall at Ten Cities in the Central and Western United States," unpublished Ph. D. Dissertation, Clark University, Worcester, Mass., 1966.
31. These studies have recently been reviewed in Ian Burton, R. W. Kates, and G. F. White, "The Human Ecology of Extreme Geophysical Events," to be published.

32. T. F. Saarinen, "Attitudes Toward Weather Modification: A Study of Great Plains Farmers," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modifications, op. cit.*, pp. 323–328.
33. W. R. D. Sewell and J. C. Day, "Perception of Possibilities of Weather Modification, and Attitudes Toward Government Involvement," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification, op. cit.*, pp. 329–346.
34. Peter R. Gould, "Man Against His Environment: A Game Theoretic Framework," *Annals of the Association of American Geographers*, vol. 53, 1963, pp. 290–297.
35. J. G. Nelson and A. R. Byrne, "Man as an Instrument of Landscape Change: Fires, Floods, and National Parks in the Bow Valley, Alberta," *Geographical Review*, vol. 56, No. 2, April, 1966, pp. 226–235.
36. See Reid A. Bryson, "Is Man Changing the Climate of the Earth?" *Saturday Review*, April 1, 1967, pp. 52–55.
37. The most comprehensive review of this subject is C. W. Thornthwaite, "Modification of Rural Microclimates," in W. L. Thomas, ed., *Man's Role in Changing the Face of the Earth*, University of Chicago Press, Chicago, Ill., 1956, pp. 567–583.
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40. Edward A. Ackerman and George O. Löf., *Technology in American Water Development*, John Hopkins Press, Baltimore, Md., 1959; and "Weather Modification and Public Policy," in Henry Jarrett, ed., *Science and Resources*, Johns Hopkins Press, Baltimore, Md., 1959, pp. 54–62.
41. Athelstan Spilhaus, "Sea and Air Resources," *Geographical Review*, vol. 44, 1954, pp. 346–351, and "Control of the World Environment," *Geographical Review*, vol. 46, No. 4, 1956, pp. 451–459.
42. Most of these studies have related to the influence of weather on airline operations. See, for example, W. Boynton Beckwith, "Impacts of Weather on the Airline Industry: The Value of Fog Dispersal Programs," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification, op. cit.*, pp. 195–208; E. Bollay and Associates, Inc., *Economic Impact of Weather Information on Aviation Operations*, final report to the Federal Aviation Agency, Washington, D.C., 1962; U.S. Weather Bureau, *A Preliminary Analysis of the Effects of Weather on Airport Traffic Flows, Airport Capacity and Acceptance Rates*, Federal Aviation Agency, Washington, D.C., 1961; and Elden J. Weigman, *Analysis of Wind and Weather Factors on the New York-London Air Route for Peak Traffic Day of August 22, 1962*, Stanford Research Institute, Menlo Park, Calif., 1963. A few studies have examined the influence of weather on railway operations. See, for example, B. J. Wintle, "Railways Versus the Weather," *Weather*, vol. 15, 1960, pp. 137–139.
43. See, for example, J. A. Russo, Jr. et al., *The Operational and Economic Impact of Weather on the Construction Industry*, The Travelers Research Center, Inc., Hartford, Conn., 1965; and P. W. Roberts, "Adverse Weather: Its Effects on Engineering Design and Construction," *Civil Engineering*, vol. 30, June 1960, pp. 35–39, 44–47, and vol. 33, May 1963, pp. 50–54.
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Review of Agricultural Economics, vol. 17, No. 3, 1964, pp. 113–119; Mary T. Petty, "Weather and Consumer Sales," *Bulletin of the American Meteorological Society*, vol. 44, No. 2, February 1963, pp. 68–71; and A. T. Steel, "Weather's Effects on the Sales of a Department Store," *Journal of Marketing*, vol. 15, No. 4, April 1951, pp. 436–443.

45. For discussions of types of analytical tools required, see Edward A. Ackerman, "Economic Analysis of Weather: An Ideal Weather Pattern Model," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification, op. cit.*, pp. 61–76; and James R. Hibbs, "Evaluation of Weather and Climate by Socio-Economic Sensitivity Indices," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification, op. cit.*, pp. 91–110. See also R. R. Rapp and R. E. Huschke, *Weather Information: Its Uses, Actual and Potential*, The RAND Corp., Santa Monica, Calif., 1964; and Richard R. Nelson and Sydney A. Winter, *Weather Information and Economic Decisions: A preliminary Report*, The RAND Corp., Santa Monica, Calif., 1960.
46. See Thomas W. Langford, Jr., "A Proposed Model for the Evaluation of Economic Aspects of Weather Modification," in Appendix X, Part 2 of this volume.
47. See James D. McQuigg, "A Simulation Model for the Study of Surface Temperature Modification," in Appendix X, Part 4 of this volume.
48. See M. M. Hufschmidt and M. B. Fiering, *Simulation Techniques for the Design of Water-Resource Systems*. Harvard University Press, Cambridge, Mass., 1966.
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54. See Reid A. Bryson, *op. cit.*

Appendix III

NEEDS FOR RESEARCH ON ECOLOGICAL ASPECTS OF HUMAN USES OF THE ATMOSPHERE

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Any recognizable unit of landscape—a lake, a stand of pines, a city park—includes a variety of plants and animals living together, competing, and interacting with each other and with their environment. Such an association of plants and animals, together with the non-living topographic, soil, and climatic factors that circumscribe their existence, is an ecosystem. Man is an essential component of practically all ecosystems, and there are few that have not been appreciably modified by man's activities. The spectrum of change extends from the artificiality of large cities and intensively cultivated rice paddies to wildernesses almost untouched by man. Man's use of atmospheric resources is perhaps as pervasive as any other of his activities in affecting the whole range of natural and artificial ecosystems.

Prediction of the effects of weather modification and of atmospheric pollution on natural and artificial ecosystems provides essential data for balancing the costs to society as a whole of specific human uses of the atmosphere against the benefits. The benefits are normally weighed and emphasized by proponents of new programs; and the immediate direct and indirect costs of carrying out such programs quickly become evident at the stage of operational planning. Unintended and unwanted effects on plants and animals of interest and value to man are likewise a part of the cost of weather modification programs.

Some of these effects may have directly measurable costs, as when changed weather patterns trigger an outbreak of insect pests. In other cases, the effects may be mostly on those plants and animals which lack a specific monetary value, but which contribute to the quality of living for a growing segment of the public. In an era when the central problem in the economic development of advanced societies is not how to avoid scarcity but how to distribute abundance, these amenity values deserve more attention than was appropriate in an earlier stage of national development.

Ecological knowledge has not yet reached the stage where reliable predictions can be made of the probable effects of specific changes in environmental variables on plant and animal communities. Because of the inherent variability of ecological processes, it is unlikely that strictly deterministic predictions of this sort can ever be made. However, a great deal of information has been collected in the last sixty years on the relations between organisms and environment. These data have not generally been organized into predictive models useful for assessing the effects of environmental change on whole ecosystems. This now appears possible, at least in a preliminary way. The resulting models can then be used to guide additional field and laboratory research.

Weather modification is a specific means by which man proposes to alter his environment on a large scale, and in a manner which is at least roughly quantifiable. As such, it is a valuable case study to point the way toward procedures for predicting the impact of other, less directly quantifiable modifications of environment. The methods used in successfully predicting how selected ecosystems will respond to changes in weather parameters should be adaptable to predicting effects of such human uses of the atmosphere as waste disposal, as well as to predicting changes likely to result from man's other activities on land and in the oceans.

Major Questions

Several types of questions may be asked about unintended consequences of human use of the atmosphere. The first class of questions deals with the effects of planned weather modification on those plants and animals that are not the primary targets of the operational program. The prediction of outbreaks of insect and vertebrate pests and of plant and animal diseases triggered by changes in weather patterns is in this category. Similarly, ecologists should be able to anticipate the spread of weeds and of undesirable animals into new habitats made hospitable by weather modification. Possible undesirable side effects are usually emphasized in ecologists' discussions of weather modification; but conditions may equally well be improved for species of animals and plants considered desirable by man, and rendered less suitable for some undesirable organisms.

Increased precipitation may set off accelerated erosion at the same time that greater plant cover resulting from the increased precipitation reduces the likelihood of erosion. This complex interaction is subject to ecological analysis. The vegetation and the animal populations of mountain watersheds may be changed in varying degree by programs aimed at increasing runoff into streams and reservoirs; forest tree growth may be accelerated at the same time that overwintering elk are hampered by deep snow. Changes in biological productivity and in rates of energy flow are likely in watershed ecosystems that are the target of weather modification programs. These changes also need to be evaluated.

A second major class of ecological problems related to man's use of the atmosphere has to do with the consequences of air pollution. It is becoming increasingly obvious that a whole range of adverse effects is associated with use of the atmosphere for waste disposal. Many pollutants have a direct toxic effect on plants and animals. Some of these effects are highly selective.

Some lead to substantial changes in the composition and functioning of ecosystems, perhaps far from the source of the pollution. Among the chemical pollutants that need additional study is the silver added to the environment in low concentrations during cloud seeding operations. Little is known of the biogeochemistry of this highly toxic element.

Land management activities, waste disposal in the atmosphere, and burning of fossil fuels add dust, particulate combustion products, and carbon dioxide to the air. These contaminants may be sufficiently abundant to change the weather over areas as large as a continent, bringing a whole chain of unanticipated consequences. Ecologists are interested not only in prediction of these consequences, but also in how ecological processes of vegetation influence the carbon dioxide balance of the earth and the control of surface dust.

A third class of questions is related to the preceding two: which of the predicted effects are reversible and which are not? Extinction of a species as a result of weather modification or air pollution is irreversible. An irreversible effect involves quite different social and biological values than those associated with such reversible changes as a short-lived outbreak of harmful insects that can be brought back under control by ending the weather modification program which triggered the multiplication. Of course, some ecologists would claim that no substantial change in a functioning ecosystem is fully reversible: this is one of the problems for investigation. A difference in degree of reversibility is certainly to be expected, depending on whether the atmospheric change extends over one, two, or many years. This problem also needs to be evaluated.

Status of Ecological Research

To date, ecologists have been primarily concerned with describing the structure of ecosystems, and with identifying the responses of individual organisms to environmental variables. We now have a reasonably good understanding of the individual components of many communities and of their spatial relations to one another; and we know to some extent how isolated organisms respond to variations in their environment. However, we have only the rudiments of a theory of how the components of a complex ecosystem interact at the community level in response to changes in environmental variables.

Nevertheless, ecology is changing rapidly from a purely descriptive to a predictive science, largely because of the accumulation of a critical mass of descriptive knowledge, accompanied by synthesis of this knowledge into conceptual models of ecosystem function. Completion of this synthesis must rely heavily on the new tools of systems analysis and data processing with high-speed computers—tools which so far have been exploited only in a superficial way by most practicing ecologists. The theoretical models thus derived will then be tested and further refined through field and laboratory observation and experiment.

The situation in ecology is in many respects analogous to that in meteorology, where the combination of an accelerated flow of observational data and progressive improvements in computer models of the atmosphere, rather than wholly new theory, is leading to a much better understanding of atmospheric processes than was possible a decade ago. Ecologists, however, have lagged substantially behind meteorologists in their data collection programs and in their acceptance of the new methods made available by the coming of the computer. Implementation of the forthcoming International Biological Program (National Academy of Sciences, 1967), may do much to accelerate development in both these areas.

Future Directions of Research

The following discussion emphasizes ecological effects of weather modification, rather than the effects of air pollution and other human uses of the atmosphere. Man modifies local weather, not just by planned interference with atmospheric processes, but also by unplanned interference: by destroying vegetation, building cities, and in other ways altering the reflectivity, emissivity, water balance, carbon dioxide balance, and dust retention characteristics of the earth's surface. Such unintended changes are highly significant in many areas. Research on the effects of unplanned as well as planned modifications of the atmosphere needs to be intensified.

A comprehensive review of the ecological and agricultural literature to identify useful generalizations is a desirable first step in developing a predictive model of the ecological implications of weather modification. Such a review is now being undertaken at the University of Michigan as a contribution to the work of this Task Group.

Ecologists have made few direct efforts to predict the effects of planned weather modification. They have devoted much time to unraveling the history of climatic change, particularly climatic change since the Pleistocene, and to describing the effects of such change on the distribution of plants and animals. However, these data for the most part are so fragmentary and circumstantial as to be of little use in predicting the effects of the comparatively small and short-term climatic changes anticipated from weather modification programs. Both the time scale and the magnitude of the changes studied by paleoecologists are substantially greater than those of interest here.

An exception is likely to be the work of those tree-ring analysts who have attempted to use variations in the width of tree rings to infer variations in past weather. In doing so, they have been forced to develop models that look backward in time; their methods and results will probably have application to the problem of predicting the ecological effects of future weather change.

The most promising current source of data for developing a predictive model is the extensive literature dealing with the effects of weather and climate on existing plant and animal communities. Most of these studies were undertaken for explanatory rather than for predictive reasons; when interpreted as a group, however, they may lead to useful qualitative inferences about the likely effects of specific weather modification programs. The review now in progress is intended to set up a series of relatively simple hypotheses about likely responses of different kinds of ecosystems to changes in weather patterns that seem technically feasible. These hypotheses can then serve as a basis for future research. As an example, there is evidence that the effect on vegetation of a given percentage-increase in precipitation will generally be greater in a semiarid climate than in one that is either very wet or very dry.

Future research must necessarily combine detailed field and laboratory investigations with large-scale computer models of the structure and function of ecosystems. Computer models are particularly well adapted to dealing with problems that are presently beyond the range of analytical solution because of their size and complexity, or because they cannot be solved effectively by experimentation on actual systems. Full-scale ecosystems have both of these characteristics: they are large and complex, and they discourage certain experimental efforts because of the time required for significant changes to occur and results to emerge. Hence, computer models are well suited to dealing with problems of full-scale ecosystems.

Computer models however, are only as good as the data that go into them, and only as good as the underlying functional relationships upon which they are based. Ecological knowledge is deficient in both these respects; hence, active field research and data collection must accompany intensive efforts at model construction. Ecological models are principally useful for suggesting fruitful lines of field research and for eliminating unfruitful hypotheses; they are in no sense an end in themselves.

The principal objective of computer models of the effects of weather modification on large-scale ecosystems is best described as sensitivity analysis. From available data on weather factors and associated vegetation and animal responses, classes of organism-weather systems highly sensitive to relatively small changes in specific weather parameters can be identified. Conversely, those ecosystems relatively insensitive to such changes can be characterized. Closely related to this problem is that of determining how much of a change in a specific weather parameter (say, February-to-April precipitation) is required to induce a recognizable change in a particular plant and animal community. This is especially important when the ecosystem change is indicated to be irreversible.

There are several related and complementary approaches to this sort of sensitivity analysis. The only one used to any real extent so far by ecologists is the family of methods built around regression, analysis of variance, and other conventional agricultural statistics. Although still highly useful, this approach presents a number of difficulties, which will be discussed later.

A second approach is system simulation. This technique is exemplified by the watershed models of Crawford and Linsley (1966), which imitate the hydrologic behavior of small stream basins. Known functional relations among variables are incorporated into a system of equations, perhaps numbering in the thousands; these are successively refined and tested against observational data until they adequately reproduce the behavior of the system under inputs observed to have occurred in the past. Then the inputs are varied, perhaps outside their normal range, or in patterns and sequences not previously encountered. Once a successful model has been set up, hundreds of combinations of inputs can be run through the computer in a few seconds at little cost. Such a simulation system can be extended to include ecological data.

A major obstacle to developing effective ecosystem models is the relative unavailability of data. Ecologists in many geographical areas are making relevant observations in the course of their personal research; but these observations are seldom available to the general biological community. A mass of useful data is stored in the files of governmental agencies. Good use could probably be made, for example, of the periodic range surveys made by the U.S. Forest Service, Bureau of Land Management, and Soil Conservation Service. An important contribution of the International Biological Program may be the standardization of ecological data collection procedures and the establishment of central data banks accessible to all.

As Malone (1967) has pointed out, much research bearing on biological consequences of weather modification remains to be done by individual investigators or groups of investigators—by so-called "Little Science"; but the final development of ecosystem models and their validation in the field are in a different and more expensive category—"Big Science." Preliminary work can be done by small groups of university investigators. For example, a project sponsored by the Cooperative State Research Service, U.S. Department of Agriculture, is getting under way at the University of Michigan to study the kinds of models and data that will be required for successful computer modeling of the effects of weather modification on watershed ecosystems. Similar work of high quality has been done at other institutions, notably the University of California at Davis. Ultimately, though, much of this effort must necessarily be concentrated at a few national laboratories that have ample financing, field facilities, and skilled manpower, as well as adequate computing facilities and the multidisciplinary teams needed to get the most from them. Such national laboratories for ecological research do not now exist.

There is a need for intensified field and laboratory investigation of the effects on specific organisms of changes in temperature, moisture, and other environmental variables. In addition, selected natural and artificial communities should be subjected to controlled, strictly localized weather modification. Since increased precipitation is likely to be the principal initial objective of operational weather modification programs, the first experiments might involve application of artificial rain. Such experiments could yield not only better knowledge of the implications of weather modification, but also fundamental data on plant and animal population dynamics under the influence of weather.

Statistical interpretation of the results of such experiments is far from easy, however. Classical methods of multiple regression and analysis of variance are best adapted to dealing with factors that are essentially independent of one another. Elements of weather and climate interact in such a complex manner as to render analysis by many of the conventional statistical methods suspect. Furthermore, the parameters dealt with seldom meet the statistician's criteria of a normal or random distribution. New and unconventional statistical approaches may be necessary to untangle the complex mixture of causes and effects encountered in field experiments. It is noteworthy that agriculturalists and hydrologists are not prepared to specify in detail how the systems that are the target of weather modification programs will respond. Indirect ecological effects will be even harder to predict from a few field experiments.

Detailed long-term monitoring of the effects of weather modification in the field should be an integral part of an operational research program involving direct activities in the atmosphere. To quote from Whittaker (1967): "In an area in which weather is to be modified, natural communities should be selected for study and permanent plots established in them. Communities should be chosen to represent the full range of environments and major types of communities in the area, including such extreme environments as ravines, dry slopes, and exposed rock outcrops. Before weather modification, sample plots of these communities should be mapped and photographed, and measurements taken of wood rings and other indicators of plant growth rates. The plots would be restudied during and after a period of weather modification to determine changes. Control plots in similar conditions outside the area of weather modification should be sought; and for maximum value both these and the sample plots should be in areas subject to long-term protection and available for continued observation." It is urgent that such monitoring programs be established at once to accompany the large-scale field weather modification experiments of the Bureau of Reclamation and others.

Particular care must be taken in interpreting the monitoring data to account for interactions. For example, a weather modification program in a livestock grazing area is likely to induce changes in livestock use patterns that could have a powerful influence on range ecosystems almost independent of the weather modification itself. A further unavoidable disadvantage of this and other field experiments is the length of time required for significant results to become available. Fifteen years is probably a minimum time before conclusions can be drawn with any degree of certainty.

It is also important that ecological studies evaluate the consequences of decreasing as well as increasing precipitation: it is possible that cloud seeding in one area may decrease rainfall downwind.

Economic Implications of the Ecological Problem

There is no assurance that proposed uses of the atmosphere will provide benefits in man's quality of living commensurate with the costs. Even if such assurance can be given, the complex problem of achieving an equitable distribution of benefits and costs will remain. The latter include not only the direct costs associated with use of the atmosphere, but also the loss of potential satisfactions from ecosystems adversely affected by such use.

Every effort should be made to limit changes that restrict the range of future choice. Coming generations may place a higher value on certain aspects of biological environment than we do today. In an age of abundance, we should plan to maintain and enhance opportunities for choice in a future where tastes and desires may change. For this reason, very high values should be assigned to the amenities associated with natural plant and animal communities, and a high cost attached to their irreversible modification. This does not mean, however, that these natural ecosystems must be considered literally priceless or of infinite value. Research is badly needed to assign economic values to the future desires of an affluent population for natural plant and animal communities of the type that exist today.

Orthodox economic analysis can, without too much difficulty, assign monetary values to some of the more straightforward consequences of weather modification. For example, the costs of damage from an insect outbreak triggered by increased rain, or the value of accelerated forest growth, can be estimated once the economist has the relevant data from the ecologist. In other instances, where the primary values affected are the amenities associated with the presence, absence, or relative abundance of certain kinds of animals or plants in a particular area, the problem becomes more difficult. Here, some form of "social accounting" (Bauer, 1966) may be required, combining sociological studies of how people perceive their environment with ecological studies of what is biologically possible and economic studies of the values that people assign to various environmental conditions. It should be possible by these means to arrive at a rank order, if not at direct quantitative measures, of the desirability of alternative investment strategies.

Most economic decision models have been developed under assumptions of relative determinacy in the outputs. Weather modification problems involve large random components in both the weather and the biological effects. The problem of decisionmaking under conditions of uncertainty is being actively explored, but the solutions are not yet very satisfactory. What is the value of reducing uncertainty by means of long-term forecasts of weather or streamflow as compared with the value of relatively small increments of additional water or crop growth with a high associated standard deviation? How can decision models be developed that will incorporate a continual flow of relevant social, biological, and political information?

Research efforts should be made to develop a resource management model that will specify the consequences of a given set of management strategies within certain probability limits. The model should indicate when these consequences will occur and who will be affected. It should suggest how the benefits and costs might be distributed and who should be responsible for making the investment. Sets of reasonable alternatives, derived from the predictive model, can then be formulated and presented for political decision. The broader the array of opportunities set up for exploration, the greater the final range of choice will be. We do not yet have the information, either from ecology or from economics, to specify all the available opportunities. Research to provide this information will be fruitful far beyond the fields of weather modification and air pollution.

Education and Training

A major educational effort is required to develop ecologically oriented scientists capable of dealing effectively with the issues raised in this report. The shortage of such scientists is not only quantitative but also qualitative. Most ecologists have preferred to work in remote areas and, so far as possible, to study communities undisturbed by man. Few institutions are now educating students to make effective use of the analytical tools necessary to deal with man-dominated ecosystems. Emphasis in ecology at most universities is on natural communities and on observational techniques.

More emphasis should be given to graduate education in the experimental, physiological, and systems analysis aspects of ecology. Several institutions are making a good start in this field, but more need to become so involved. Strenuous efforts must be made to acquaint good graduate students with the opportunities growing out of the national effort in ecology. Perhaps the most serious obstacle to realizing the program suggested in this report is the shortage of trained people. Until that shortage is overcome, we are likely to make little progress toward quantitative prediction of the probable consequences of human uses of the atmosphere.

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Appendix IV

SOCIOLOGICAL ASPECTS OF HUMAN DIMENSIONS OF THE ATMOSPHERE

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Sociology in the broadest sense deals with the scientific study of man as a social being, his social organization and culture. While a few sociologists early in this century speculated on the ways in which the environment may shape man's institutions, no meaningful research on the possible relationship was conducted. During the period from 1930 to 1950, there appears to have been a strong negative reaction to the suggestion that man's social behavior may be determined significantly by his "natural" physical environment. In recent years, however, sociologists seem to have developed a more "open" attitude toward the possibility of this relationship. Perhaps the wide publicity given to air pollution problems in the mass media and the emergence of research on drought, floods and other natural disasters have produced some "second thoughts" on the part of sociologists. Nevertheless, a review of recent social science literature makes it clear that research on the sociological aspects of the relationships between man and the atmosphere has not yet really begun. Indeed it appears that social scientists in general are only now beginning to show serious interest in the human dimensions of the atmosphere.

Major Questions

We know very little about the relation between specific dimensions of "normal" weather variation and the various human activities in a community or region. We need to conduct research leading to a better understanding of the relation of weather variation to such factors as:

1. Incidence of illness and use of health facilities and personnel.
2. Incidence of crime, and law enforcement efforts.
3. Use of educational facilities and student performance.
4. Flow of persons and goods through transportation networks.
5. Nature of major recreational and leisure time activities.
6. Disruption and use of basic community services (fire protection; electric, water and gas distribution; and mass communications).
7. Participation in political activity (registration, voting, etc.).
8. Incidence of racial disturbances.
9. Demand for and use of welfare services.

A related question deals with the collection, dissemination and use of weather forecasts. What is the influence of weather forecasting? How do the content of forecasts and the mode and speed of dissemination relate to interpretation and use?

Man's modification of atmospheric conditions raises still another group of questions. If man has developed a set of adjustment mechanisms to cope with the atmosphere as he has perceived and experienced it over a long period of time, and that set of atmospheric conditions is altered significantly by inadvertent actions or planned efforts, some kind of readjustment is bound to occur. What are the discernible consequences of weather modification? What kinds of individual and group readjustents can be anticipated? Do individual and community responses to planned weather modification differ significantly from those to inadvertent modification (such as air pollution)?

The following outline of a possible research approach to this matter illustrates one perspective which seems feasible and potentially significant.

Longitudinal (panel) studies of community and individual response to precipitation augmentation efforts

A. Communities to be selected for study.

1. Experimental communities (Ex Com) of more than 2,500 population which will probably be affected by augmentation efforts.

2. Control communities nearby (Con Com I), matched on selected variables, not subject to modification efforts or located in any hypothetical "rain shadow," but likely to receive the same information about the efforts as Ex Com.

3. Control communities (Con Com II) matched on the same selected variables as above, but not likely to receive as much information about precipitation augmentation efforts.

B. Types of data to be collected.

1. Monitoring of mass media input about augmentation efforts: radio, TV, newspapers and magazines which have significant subscriber audiences in each community. Include news reports, editorials, feature stories, letters to editor, etc.

2. Systematic collection of data on speeches, public meetings, planning groups and "interest groups" where subject is discussed. Attend such events where possible; otherwise collect data from persons who did attend.

3. Measures of attitudes toward precipitation augmentation and perceptions of the climatological events and their consequences "before," "during" and "after."

a. Members of the "power elite" or "community influentials."
b. Sample of those "directly" affected.
c. Sample of community members not in the above categories.
d. Persons involved in planning, application and administration of the weather modification efforts.

4. Data on organized response actions by members of the community. These would include pro- or anti-efforts, such as organized letter-writing or phone campaigns, protest or support meetings, lobbying efforts, and harassment efforts of whatever type. Response actions might come from emergent groups and organizations, or from established organizations of various kinds. The efforts might be of many types: legal, openly political, *sub rosa* political, economic, educational, or general mutual support.

5. Data on actions and expressions of policy and opinion from persons involved in planning, application and administration of the weather modification efforts prior to and in the face of response actions from the community. Heavy emphasis would be placed on securing a complete picture of the on-going interaction between community members and groups on the one hand, and the "weather modifiers" on the other. The emphasis would be on *processes* and *issues* involved, rather than just on persons, groups and the specific events as they unfold.

6. Data on relatively permanent changes: community adjustment, adaption and structural change lasting at least to the end of the data collection phase. This is probably the most difficult problem for research design and implementation; but it is in many respects the most important. While measures of attitudes and perceptions about attempts to augment precipitation would provide part of the answer, the most important data would reveal power considerations generally (legal, political, economic, social). (I would envision this part of the research paralleling the type of effort seen in Philip Selznick's *TVA and the Grass Roots*.

Finally, there are many unanswered questions regarding man's perception of and adaptation to "extreme" weather events, such as hurricanes, blizzards, tornadoes and floods. Do communities which have an above-average incidence of such events develop a relatively distinct "disaster sub-culture"? Do citizens in such disaster-prone communities develop a heightened sensitivity to weather forecasts in general, or only to severe storm warnings? Or is apathy the dominant mode of adjustment? Does adaptation vary significantly among various socio-economic levels? Are communities which frequently experience such weather hazards more likely to have effective organizational mechanisms for minimizing disruption, damage and injury than those which seldom experience such extreme weather events? Can adequate "disaster preparedness" be induced in communities which seldom experience severe storms or floods? Answers to these and similar questions are both scientifically and pragmatically significant.

Recommendations

1. Planned weather modification in the form of efforts to augment precipitation is about to get underway on a fairly large scale. While it is likely that these attempts will produce only moderate increases in precipitation,

it is very much an open question as to how these efforts will be *perceived* by the population in affected areas. It is possible that a small increase in precipitation may produce a large unanticipated response. Our ignorance about the short- and long-term consequences of modification activities is almost beyond description. Therefore, research proposals dealing with the social, political and economic aspects of planned weather modification should be given high priority.

2. For better or worse, the scientific study of human social behavior has been and will probably continue to be primarily the job of the several social science disciplines—each with its own somewhat unique theoretical perspective and methodological approach. While there is a good deal of justification for this division of labor, it is also clear that there are "problem areas" where a multidisciplinary approach has distinct advantages. Examples where the multidisciplinary approach is emerging include urban and regional planning, rehabilitation of persons with medical disabilities, "war on poverty" efforts, organizational analysis, and criminology. Since social behavior is or may be influenced by the atmosphere, and since man's behavior is obviously altering the atmosphere, it would appear that a multidisciplinary approach to the study of human dimensions of the atmosphere is distinctly called for.

A multidisciplinary approach cannot be mandated, but it should be encouraged in a variety of ways. The primary and immediate need is for a center for collecting and disseminating information about activities and opportunities related to both basic and applied research on human dimensions of the atmosphere. Such a center should be established on a university campus in order to ensure ease of communication among members of all of the behavioral and atmospheric sciences. Initially the center should collect information about potential research support, relevant governmental policy, on-going research activity, fellowships and traineeships, symposia, new university programs for training, and research reports, articles and books dealing with theoretical and methodological developments in the behavioral and atmospheric sciences as they relate to human dimensions of the atmosphere. A quarterly or bi-monthly newsletter should be prepared from these materials and sent to all persons who are interested in the area or who are in positions to influence the interests of others. Such a center should be established immediately.

Another way to encourage a multidisciplinary approach is by providing funds for it. Financing for fellowships, traineeships and internships in multidisciplinary programs will encourage universities, research centers and relevant governmental agencies to develop such programs. These should be primarily, but not exclusively, at the graduate level.

Research proposals which incorporate a multidisciplinary approach should be given higher priority in the allocation of research funds than those which do not. This should be made explicit in official announcements; and, where possible, the review of such proposals should be made by professionals who do not have a narrow, single-discipline orientation.

3. Finally, since the earth's atmosphere is not the private domain of any nation, we must recognize the international aspects of the man-atmosphere interaction. Various efforts are undoubtedly warranted; but at least two require early implementation. First, yearly symposia should be planned to consider international aspects of the problem. These should be financed in such a manner that professionals from less affluent nations may attend and contribute. At least half of the meetings should be held outside of the United States.

Second, active exchange programs should be developed. These should be financed to allow less affluent professionals in the United States and abroad to participate. The exchange programs should not be limited to university-based professors, but should include other qualified persons interested in man-atmosphere relationships. The programs should provide opportunities for teaching and consultation activities, as well as for intensive research.

Appendix V

ECONOMIC RESEARCH ASPECTS OF HUMAN ADJUSTMENT TO WEATHER AND CLIMATE

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The past decade has witnessed a rapidly growing concern about the management of atmospheric resources. In many parts of the United States, air pollution has reached serious proportions, and action has been called for to deal with this problem on a national scale. Losses of property and life caused by hurricanes, tornadoes, lightning, heavy snow, and floods continue to mount. Persistent droughts in the Northeast and the desire of the Bureau of Reclamation to augment the water supplies of its irrigation and hydropower schemes in the West have led to increasing pressure for programs of weather modification and for expanded research in that field. Increasing attention is being given to the important economic effects of weather and climate on human activities.

Variations in weather and climate affect human activities in at least three major ways. First, temperature, precipitation, and wind are important elements in certain production processes. Variations in temperature and precipitation, for example, often mark the boundary between success and failure in agriculture. The amount and timing of precipitation have important effects on the operation of hydro-electric power systems. Second, the weather sometimes causes considerable losses of property and income, as in the case of wind storms, heavy snow, lightning, or hail. Third, the atmosphere is one of the most dynamic elements of the nautral environment, changing constantly in composition. The timing and the magnitude of these changes are difficult to predict. Uncertainty, therefore, is a major factor affecting human use of the atmosphere.

Man has tried to cope with weather variations in several ways, ranging from taking no action at all to attempts to alter the processes which produce the weather. For many economic activities weather variations are unimportant, and *no action* is called for to accommodate changes in precipitation, temperature, or wind. For some activities, however, such changes are critical.

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In these activities, commonly referred to as "weather-sensitive," attempts have been made to accommodate weather changes both by reducing the uncertainty of their occurrence and by devising techniques to offset adverse effects. Weather forecasting is one attempt to reduce the uncertainty of weather events. Flexible production schedules, drought-resistant crops, ground-zero landing devices to overcome limited visibility at airports, and home heating and air conditioning devices are examples of efforts designed to offset the effects of weather variations.

For the most part, man has concentrated his attention on *accommodating* the weather. But he has also tried to *change* the weather. So far his success in changing the weather seems to have been quite limited. Even though we have now entered the modern era of scientific weather modification, possibilities of accomplishing changes either on a consistent basis or on a large scale are still some way off. Nevertheless, many of those involved in the development of weather modification techniques believe that much will be accomplished in the next few years. Considerable sums of money are now being invested in research and development to advance the weather modification frontier.

There are three major alternative adjustments to the weather: reducing uncertainty through improvement of weather information; devising techniques to offset the impact of weather; and developing means to alter the weather. Given these alternatives, what factors need to be taken into account to determine which approach is economically most efficient? At least three questions seem pertinent in this connection.

Major Questions

1. *Which activities are sensitive to weather variations and in what degree?* As noted earlier, variations have major effects on certain economic activities. In some cases the effects are indirect, as when the weather influences one economic activity and the results are passed on to other activities.

2. *To what extent are the various adjustments technically feasible?* Much progress has been made in the past two decades in understanding the changing composition of the atmosphere, and as a result the accuracy of weather forecasting has improved. This has made it possible for those engaged in weather-sensitive economic activities to reduce the degree of uncertainty in their decisions, but it has not removed uncertainty altogether. Then, in some activities, even though more accurate weather information is available, it is still very difficult to make short-term adjustments. Some production schedules, for example, are relatively inflexible in the short run. In these and other cases, techniques for offsetting the effects of weather may not be feasible. In regard to techniques for modifying the weather, present capabilities seem confined mainly to augmenting precipitation in orographic areas, dispersing cold fog, and suppressing lightning.

3. *What are the gains and costs of each of the alternatives?* Gains presumably would be expressed in the value of increased output over what

would be possible without a given adjustment. Costs would include not only the direct costs of the techniques (such as those of operating a weather forecasting program, developing drought-resistant crops, or developing weather modification techniques), but also the associated costs of adopting them. The cost of adopting a weather forecasting program, for example, is not confined to the cost of supporting the U.S. Weather Bureau, but extends to the expenditures of its clientele in using the information provided.

Costs and benefits often extend beyond those who make decisions to adopt a particular alternative. In the case of weather modification, for example, the decision may be made by one farmer, but the resulting modification may have beneficial or adverse effects on his neighbors. These external effects are either windfall gains or uncompensated losses; and they must be taken into account in appraising the overall efficiency impact of adopting a given alternative adjustment.

In addition to the efficiency effects of procedures to adapt to or modify weather, there are income distribution effects, by occupation, income class, and region. Improved forecasting, for example, may not only increase agricultural output, but may also induce shifts in production to different crops and different areas. The area distribution of outdoor recreation expenditure can certainly be affected by any substantial improvement in forecasting or by major changes in weather modification capabilities. Reduction or diversion of tropical storms may change the composition of economic activity over wide areas where levels and distribution of precipitation are affected. It is vitally important to distinguish efficiency and distribution effects, and to assess as fully as possible the economic implications of both.

Progress in Economic Research Relating to the Human Use of the Atmosphere

Thus far economists have shown only minor interest in the economic aspects of the human use of the atmosphere. Several reasons account for this. First, it is only relatively recently that major problems have arisen in the management of atmospheric resources or, more accurately, that they have become a matter of real public concern. Second, until recently, not enough was known about the atmosphere to specify accurately the physical dimensions of weather variations or the possibilities of modifying the weather and thus to provide alternatives for evaluation. Third, the systematic development and application of economic principles in the whole field of resource management are relatively new. Nevertheless, economists have made some important contributions towards identifying economic impacts of weather variations and evaluating alternative adjustments to the weather.

Economic Impacts of Weather Variations

Much of the attention relating to economic impacts of weather variations has been devoted to the influence of weather on agriculture. Economists have long been interested in the relationship between variations in precipitation and temperature, and variations in agricultural output and income; and a rapidly growing body of literature has been devoted to this subject.[1] Important contributions have been made toward the development of theory[2] and techniques of measurement[3] in this regard. Studies have been undertaken relating to particular crops[4] and to particular weather variables.[5]

Despite this progress, however, much remains to be done before the influence of the weather on the agricultural sector of the economy can be fully assessed. It is possible to assess the impact of a given weather change on certain crops in a given region, but we are still not at the stage where we can estimate the effects on all crops or agricultural activities in that region. Nor can we trace accurately the impacts of a given weather change on activities connected to agriculture.

A second group of activities that seems especially sensitive to the weather is the transportation industry. Heavy snowfall, floods, winds, and lightning interrupt normal traffic patterns of airlines, railroads, and highways; and these interruptions result in major losses of income as well as inconvenience to shippers and travellers. So far, most of the research done in this area relates to the airline industry. Several studies have been undertaken by the airlines or their consultants,[6] and by various government agencies. These have sought to identify the losses caused by particular weather phenomena, such as fog, snow or wind. A few studies have investigated the impacts of these phenomena on the use of highways and railways; but no general model has been developed thus far which would permit an accurate assessment of the impacts of a given weather variation on the national railway or highway systems or even the overall effects within a region.

The construction industry is another activity which is especially sensitive to weather changes. Only a few studies of weather impacts on this industry, however, have been undertaken.[7]

It has often been noted that retail sales appear to be influenced to some extent by variations in the weather. A few studies have examined the effects of given weather changes on the sale of particular products and on particular types of retail outlets. As yet, however, no model has been developed to estimate the influence of different weather variables on retail trade.

Another activity influenced by variations in the weather is the tourist trade. Extended periods of precipitation in the summer often result in severe reduction of normal tourist traffic on holidays and weekends. Lack of snow reduces the revenues of ski resorts. Although much research has been undertaken to identify the value of recreation,[8] few systematic attempts have been made to determine the influence of various weather elements on the recreation industry or the tourist trade.[9]

Techniques of Evaluation

Techniques are required for weighing each of the various alternative adjustments against each other. Although little work has been done that relates to the weighing of these alternatives *per se*, a considerable amount of research in the general field of economics can be applied toward this end. Principally, this research deals with techniques of benefit-cost analysis, systems analysis, and with the economics of research and development.

Benefit-cost analysis can be a very useful tool in weighing the merits of alternative courses of action, particularly where the public sector is involved. Much work has been done in recent years to refine its theoretical basis,[10] and to broaden its field of potential applications.[11] Progress has been made with some of the more difficult problems of applying the analysis—notably in the treatment of risk and uncertainty, the treatment of time, and the identification and measurement of externalities. A few attempts have been made to apply the technique to weather-related problems, such as air pollution[12] and weather modification.[13]

Potentially useful work has also been undertaken in the field of systems analysis and operations research. Some attempts have been made to apply the results of this work to weather-related problems, e.g., the evaluation of weather information systems.[14] Much of this work, however, has been highly theoretical, and further applications await empirical studies of the manner in which weather information is actually used. There is evidence, for example, that different industrial managers interpret weather information in vastly different ways, even within the same plant.[15]

Economists have also become increasingly interested in the evaluation of investment in research and development. They have begun to question whether the returns on certain types of research and development justify their costs. Theoretical frameworks have been developed for this purpose, and these have been applied to investment in research on such matters as defense, oceanography, highways, and education.[16] A few attempts have been made to evaluate programs of research in the atmospheric sciences, e.g., the weather satellite program;[17] but some of these efforts have been too simplistic to be useful.[18]

Priorities for Future Research

Bearing in mind the problems raised by the increasing use of the atmosphere for the disposal of wastes, the growing toll of losses caused by severe weather events, and the development of programs to modify the weather—and noting also the present status of research on the economic aspects of these problems—what priorities might be assigned to future research in this field? Four major topics are suggested in this connection.

1. The Relationships Between Weather Variations and Output and Income in Different Economic Activities

Identifying the impact of weather on various economic activities is a necessary first step in evaluating alternative adjustments to the weather. The major relationships between weather variations and output and income in different economic activities must be determined. Only then will it be possible to assess for specific activities the potential merits of weather forecasting programs; the needs for loss-reductions as related to severe weather events; the feasibility of different techniques for offsetting the effects of the weather; and the costs and benefits of weather modification programs.

Studies need to be undertaken not only to identify more precisely the impact of weather on different economic activities, but also to determine the manner in which the effects on particular activities are transmitted to other activities. These studies will require empirical investigations of various weather-sensitive processes and the development and/or adaptation of analytical techniques to trace impacts through the economic system. Techniques which may be useful include various types of economic models, such as input-output models, simulation models, and linear programming models. Present techniques, however, need to be examined to determine whether they can be adapted to include weather as an input (or as a cost-producing factor), or whether new techniques need to be evolved.

2. The Evaluation of Alternative Adjustments to the Weather

Benefit-cost analysis provides a useful framework for weighing the economic merits of alternative courses of action. Thus far it has been applied only to a limited extent in evaluating various adjustments to the weather, such as weather information programs, techniques for offsetting the effects of the weather, or weather modification programs. While it is probably too early to think about a generalized model to weigh the economic merits of alternative adjustments to the weather, the application of benefit-cost analysis to decisions in this field can be furthered by undertaking research on the following topics.

First, a number of *pro forma* studies should be undertaken to identify *all* alternative courses of action and their potential side-effects in a given area. Even if the parameters cannot yet be given numerical coefficients, a framework of analysis for these limited purposes will be invaluable in furthering research on economic evaluation and in developing intelligent programming in the action agencies concerned with management of atmospheric resources.

For example, decisions will need to be made about investment in weather modification programs. Such programs are attractive particularly because of their low capital costs and short-run flexibility. But weather modification is not the only way in which the desired benefits may be obtained. In almost every case, there are readily available alternatives: extensions to existing irrigation systems; creation of new irrigation systems; desalinization; or adjustment of agricultural techniques to use less water and to minimize the effects of irregular water supply. No general model can encompass all of these possibilities and remain manageable; but *ad hoc* models geared to the specific alternatives in a specific area can be invaluable in assuring that a weather modification program not only meets the tests of technical feasibility and of benefits in excess of costs, but also provides greater net benefits than any other alternative.

Second, empirical studies should be undertaken to compare the relative economic merits of pursuing a given objective in each of several areas. For example, weather modification efforts have been concentrated so far in semi-arid regions, where interest in increasing precipitation in most active. From an economic standpoint, however, it is possible that modifying precipitation patterns in relatively humid areas to provide marginal increments at the right time may prove to be much more productive. This is, again, not a question that can be answered in theoretical terms; it requires specific empirical investigation.

Third, more research needs to be undertaken to identify the external effects of alternative adjustments to the weather, and especially those of weather modification. Determining potential external effects depends upon increased knowledge about the impact of weather variations on each economic activity. It also depends upon more specific information about the physical effects of weather modification, both spatially and temporally. Does additional precipitation here mean less precipitation elsewhere? Does it mean less precipitation here in the future? If weather modification merely results in a special or temporal redistribution of a fixed quantity of precipitation, its attractiveness may be reduced. Investment in weather forecasting also has external effects, as in production and income changes for activities related to weather-sensitive activities.

The universal character of the externality problems associated with weather forecasting and modification suggests the need not only for identifying and quantifying these effects, but also for considering possible compensations that would permit projects with significant net economic benefits to be carried out despite the fact that there will inevitably be some "losers." It is possible that applied research can provide some guidance as to the extent to which a system of charges and payments might induce weather modifiers to plan their activities to minimize undesired external effects. The work of Kneese and others in water quality management suggests that this is fertile field for public policy considerations.

3. Opportunities Where Scientific Knowledge and Efforts Are Still in the Embryonic Stage

Much can be accomplished by specifying activities which might realize significant economic gains from alternative adjustments to the weather, even without determining the present technical feasibility or costs of such efforts. Major storm modification may lead to important economies. The possible relationships between peak wind velocities and incremental damages suggest this. Major storm modification may also minimize the many external effects produced when storms are diverted or prevented entirely, thus creating problems of distribution and quantity of precipitation. The enormous political and administrative difficulty of dealing with such problems has diverted attention from the more intriguing possibility of reducing damage with minimal external effects by storm modification (rather than complete diversion or prevention). Experience in the flood control field, where analogous problems of stochastic occurrences of severe damage are involved, suggests that compulsory flood insurance, flood plain zoning, and other procedures not involving direct modification of the flood process may be the most efficient ways of minimizing social costs in many cases. The same type of approach may set ceilings on benefits from storm modification, and should be investigated carefully as part of any systematic attack on the problem of storm damage.

4. Economics of Information

During the past twenty years, increasing investments have been made in research devoted to understanding the atmosphere and to the development of weather forecasting programs and weather modification techniques. So far, however, little attempt has been made to appraise the economic value of this research and development. One assumption seems to be that the value is either self-evident or at least equal to the size of the investment. Another assumption is that once available, the results of the research and development will be translated into action without further cost or delay.

There is reason to question the validity of these assumptions. Can it be assumed, for example, that there is necessarily an economic payoff from investment in research, and particularly basic research? Even if there is a payoff, experience suggests that it often takes a long time for such results to find their way into operational programs. Techniques for modifying the weather, for example, may be available for many years before they are put into practice. Similarly, the capability for improving the accuracy of long-range forecasting may increase, but it does not necessarily follow that many people will use the information. Nor is it clear that those who use forecasts will do so in the way that the Weather Bureau assumes they will. The uncertainty about the manner in which information may be used becomes especially critical when programs of major storm modification are being considered. Studies of weather-caused disasters show that even if people are informed about the probability of a weather event, they may take no action to deal with it.

Studies are needed on the economics of information, and on research and development programs in the fields of weather forecasting and weather modification. Without such studies, the value of these programs can only be a matter of guesswork.

Manpower Requirements

It has become customary, whenever the Federal Government plans expansion of a scientific research and development program, to argue that if enough money is available and the program is made sufficiently attractive, the necessary number of specialists to man the program will always come forth. Unfortunately, when several programs drawing on the same pool of manpower are expanding at the same time, this generalization may not hold. The long-run interests of the Nation may not be served if expanding research and development programs strip the universities of the qualified personnel needed to train future specialists in the field.

A well-conceived and well-financed framework that will support a continuing research *program,* rather than a series of scattered projects, would offer sufficient attraction to bring competent social scientists into the field. Economists would not necessarily need to be trained as weather modification specialists; they might well make their most effective contributions as competent general economists with a specific (but not sole) interest in the field of resource economics.

A successful research effort on the economic dimensions of the human use of the atmosphere hinges in part on opportunities for resource economists to gain an understanding of weather technology in general. Funds might be provided to enable such economists to take a year to work closely with physical scientists on a problem relating to management of atmospheric resources. Much could also be accomplished by interdisciplinary seminars and symposia. In addition, training grants would enable graduate students to develop an interest and competence in the economics of the atmosphere.

Funds are required not only for training purposes, but also for research. At present, only a small amount of money is available for this purpose through the National Science Foundation; and only recently have the action agencies sponsored research in this field. Funding at several times the present level is required if the research effort recommended in this report is to be undertaken.

FOOTNOTES

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Appendix VI

NEEDS FOR RESEARCH ON THE POLITICAL ASPECTS OF THE HUMAN USE OF THE ATMOSPHERE

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Major Questions

How will human welfare be affected by efforts to modify atmospheric conditions?

The atmosphere in a state of nature behaves as a dynamic system which sustains a flow of both goods and bads when measured by the criteria of human evaluation. Hail, lightning, tornadoes, hurricanes, and other atmospheric phenomena can be the source of major destruction to human values. On the other hand, the atmosphere performs the essential work of distilling and transporting nearly all of the potable water supplies found upon the land masses of the earth. A major political question is whether the developing technology of weather modification can be used to modify atmospheric conditions to increase the yield of precipitation under certain conditions and to decrease the magnitude of turbulence and the yield of bads under other conditions. An economic advance in human welfare can occur wherever human intervention increases the yield of goods in excess of aggregate costs or decreases the yield of injuries or bads with the same net result.

Difficulties arise from circumstances that a good at one time and place may create injuries and losses at another time and place. Increased precipitation at the time of harvest may be as detrimental to agriculture as decreased precipitation during the early growing season. The harvest of one crop, cherries for example, may coincide with the growing season for many other crops. Men may be willing to take the calculated risk and tolerate the losses suffered by an "act of God," but they may not be as tolerant of losses suffered as a consequence of the actions of other men.

Many existing forms of human endeavor have taken account of climatic probabilities in making locational decisions. What are the costs of dislocation if probabilities bearing upon climatic conditions are altered by human action? Who pays for the costs; and who reaps the benefits?

The atmosphere is used as a transportation and communication medium that serves a large variety of other human utilities and disutilities. Much of modern industry is based upon processes of combustion to provide the principal sources of energy and to perform many of the processes of physical and chemical transformation which serve as means of production. These processes normally depend upon the atmosphere as the principal source of oxygen to supply the combustion process and to carry away the load of waste gases and other waste chemicals which can be discharged into the atmosphere.

Humans may have a relatively low threshold in response to some chemicals wasted into the atmosphere and have a relatively high tolerance for other chemicals. Highly toxic compounds discharged by metallurgical industries, for example, may have the effect of producing substantial damages within the immediate vicinity of a plant. In other situations similar wastes may become toxic only when higher thresholds are reached. Toxic by-products may be also released by photosynthetic chemical transformations which take place under natural atmospheric conditions. Radioactive wastes produced by nuclear explosions are but one of the more perplexing problems concerning the pollution of the atmosphere through its function as a medium transport.

In addition to these transport functions performed by the atmosphere we should not fail to recognize that "air transport" with the development of the "airplane" has become a major mode of commercial transportation in the movement of persons and products about the earth's surface. The uses of the atmosphere for such purposes must be taken into a proper accounting in dealing with the use and development of atmospheric resources. The development of air transport which moves at supersonic speed will also be accompanied by atmospheric disturbances in the form of high-intensity sound waves which may be capable of causing substantial damages as well as producing inconvenient annoyances.

These incomplete and sketchy examples of the human uses of the atmosphere merely serve to indicate the lack of conscious self-awareness which exists in relation to the use and development of atmospheric resources. We need a more complete inventory of present uses made of the atmosphere and an assessment of the future potentialities of pending uses which can be derived either from existing technologies or from pending technological developments.

In any such inventory we need to know something of the magnitude of existing and potential demand in relation to existing and potential conditions of supply for the various different demands and of the pattern of inter-action among the different potential uses. What are the relative inelasticities of supply so that an increased demand or use results in an impairment of the conditions of supply? When such a condition is reached, policies of free development must begin to give way to policies of controlled development. A knowledge regarding the conditions of inter-action between demand and supply has an important bearing upon the choice of policies to maintain demand-supply equilibrium at the tolerances which permit an optimal pattern of development.

We also need to know something of the pattern of inter-action among the different potential uses of the atmosphere and the effect that these patterns of inter-action have upon the general resource economy of the atmosphere. How, for example, will efforts at weather modification to reduce storm damage affect the atmosphere's yield in the precipitation of water, its use for air transportation, and its capacity to discharge diverse waste loads? Conversely, how do efforts to increase the atmospheric yield in precipitation of water affect storm patterns and intensities and the other patterns of use which form a part of the total configuration of demands made upon the atmosphere?

Inter-action among uses implies interdependencies which must be taken into account by any enterprise or agency undertaking programs concerned with the development of atmospheric resources. Where one type of use impairs, excludes, injures or destroys an alternative use, serious problems of conflict are apt to arise. Where one type of use facilitates another, problems may also arise in assuring the appropriate level of development which will take account of the joint yield or payoff for both purposes.

What are the essential characteristics of atmosphere as a resource system which must be taken into account in the organization of an appropriate enterprise and management system?

The atmosphere as a natural resource appears to meet all of the criteria of a common-pool, flow resource system. The resource is not easily isolatable except within the controlled air-space of a shelter, and as a consequence it cannot be easily bounded or contained. The resource in most of its aspects cannot be subject to a high level of control. Spill-over and interdependency effects abound among the diverse joint and alternative uses which can be made of the atmosphere.

The atmosphere as a common-pool, flow resource has some of the most perplexing characteristics of any of the common pool resources, at least as perplexing as those of the oceans. First, the atmosphere has no distinct and definitive boundaries for distinguishing sub-units. Water resource systems are formed into natural watersheds which provide definitive boundary conditions for organizing management programs. There are no such boundaries for easily characterizing micro-climates, airsheds and sub-systems in the atmosphere. Instead the atmosphere is a dynamic system subject to changing velocities and patterns of flow under varying conditions of pressure and carrying capacities.

Yet, the field of effects or the scope of the consequences which flow from any course of action affecting atmospheric conditions is not without limits. It is doubtful, for example, that air pollution from Southern California has any appreciable effect upon Santa Fe, N. Mex. Knowledge regarding the field of effects would provide us with the first tools for the specification of proximate boundary conditions applicable to atmospheric resource development. The political process will provide alternative remedies so that those who may be adversely affected can present their case and seek appropriate remedies to take account of their interests. Exposure to such actions is a necessary risk of doing business in a field of endeavor where action is taken with only limited awareness of the likely consequences.

While the risks may be high in undertaking programs of atmospheric resource development in the absence of adequate knowledge, the incentives for action may also be relatively high. An aggravated air pollution problem in southern California may call for alleviation without being able to specify the technical criteria most appropriate for defining the field of effects and of the precise community of interest appropriate to a smog control program.

The task of specifying boundary conditions appropriate to the field of effect produced by one form of action in the use and development of atmospheric resource may be quite independent of the boundary conditions appropriate to another pattern of use and development. As a result different scales of organization and different forms of enterprise may be appropriate to different types of development. It is probably not unreasonable to expect that the configuration of enterprises associated with the use and development of atmospheric resources will be at least as highly differentiated as the configuration of enterprises which are presently concerned with the development of water resources. This includes private, local, State, and Federal resource development agencies.

What enterprise-management systems are appropriate for the development of atmospheric resources?

All common-pool or flow resources which are lawfully subject to use and development by persons making independent claims upon the resource are conceived as common properties. The conception of a common property usually includes reference both to the *individual interests* in the common-pool or flow resource and to the *community of interests* which are shared in such a resource. One has reference to the elements and relationships comprising the subsets of interests; the other has reference to the universal set of interests associated with a common-pool or flow resource.

The law relating to rights in common property includes reference to concepts which imply significant variations in the methods for conceptualizing the various interests involved. The concept of *res nullius* has usually been applied to the rights of persons to make use of the atmosphere or of the ocean. This concept implies a negative community—an undefined, ambiguous universal set involved in the development of a common-property resource. On the basis of this concept the property is defined as belonging to no one and subject to use by everyone. The relationships among different users can, however, be adjudicated under equity jurisprudence allowing for the application of rules of reason in reaching equitable solutions to conflicts of interest. Some such rules were once applied in the location of windmills, for example, where the construction of a new mill might adversely affect the operation of an established mill.

The doctrine of *res nullius* is a doctrine applicable to the free development of a resource as essentially a free good. Willful injury, malfeasance, unreasonable or wasteful uses or methods of use provided the basis for governing relationships among various users without the necessity for defining the community of interests inherent in the common property situation. Much of the contemporary law regarding the use and development of the atmosphere has not advanced beyond the conceptions inherent in the doctrine of *res nullius.*

The concept of *res communes* implies an increasing capacity to define and delimit the community of interests shared by those who have established a right to use a common property. Each has a right to use, no one owns the resource in particular, but the universal set is subject to a more finite and less ambiguous relationship. The reciprocal sets of interests including both the rights to use and the limitations and obligations of use are subject to increasing specification. In the relatively simple common-pool problem such as that associated with the use of a definable ground-water basin the reciprocal property rights may be subject to determinate solution through adjudication. The rights in a common property under such circumstances can be converted into an exclusive right to a divisible share in the common property once the universal set can be discretely defined.

This solution is not readily available under conditions where public solutions are required either to undertake the management of a production program to increase the supply of goods to be derived from a resource system, to provide some good subject to public provision (i.e., a non-divisible, non-marketable good or service) or a combination of both elements. Under these circumstances a part of the universal set of interests shared among the community of interests to a common property is subject to public proprietorship in one form or another. Where public and private interests are shared in a common property resource, the law of property no longer provides an adequate solution to the organization of institutional arrangements for resource development and management. Recourse to public solutions, at least in part, are necessary and the traditions of public law bearing upon the organization and government of public enterprises become an essential element in the institutional framework for shaping public solutions.

Circumstances requiring public solutions might be met by several different alternative arrangements in the organization of an enterprise-management system. One approach would be to pre-empt and occupy the resource system under the management and control of a single public authority. Another possibility would be to consider the development of a mixed private and public enterprise system in which solutions would be taken incrementally rather than by pre-emption through a single public authority.

The field of water resource development provides the most extensive experience in the use of mixed private and public institutional arrangements for the development of a common-pool, flow resource. This experience is not directly applicable to problems concerning the development of atmospheric resources. However, many of the basic concepts can be used subject to appropriate modification to deal with the distinctive circumstances associated with the development of atmospheric resources as distinguished from water resources.

What institutional arrangements are already available to facilitate new experimental and operational programs concerned with the development of atmospheric resources?

Where institutional arrangements and production facilities are already well developed to assure rather full control over the hydrologic behavior of different river courses and watershed basins, private entrepreneurs should be confronted with minimal difficulty in undertaking weather modification programs either on an experimental or operational basis. Existing water supply agencies are the potential buyers for such services. More frequently than not these agencies are organized as public enterprises capable of sustaining a flow of revenues whether through service charges or from tax levies. Where major water producers are not free to levy a tax upon local beneficiaries, these producers are usually parties to contractual arrangements with wholesale or distribution agencies, organized as public water districts or as municipal water supply systems, which can exercise the power of taxation and provide an appropriate flow of revenues. If weather modification programs assure an incremental water supply at less cost than alternative sources of supply, minimal difficulties would be anticipated in accommodating this incremental source of supply into the production schedule of the primary water production agencies in response to normal growths in demand. In many areas of the western United States where demands for water are relatively high in relation to local supplies, whole watershed areas are held in public ownership where water production is a principal element in the watershed management program. These circumstances should tend to minimize conflict over actions to increase precipitation and the normal operations of diverse land owners. In turn, reservoirs operated by the principal water production agencies would be available to minimize the risks of flooding in the lower flood plains of a river system and of producing damages for which weather modifiers might be held responsible.

Experience gained on the basis of these more fortuitous circumstances should serve as a basis for the expansion of weather modifications programs to increase the yield of precipitation under other conditions as the demands for water grow. Private enterprise in weather modification is not precluded as long as public agencies are available to function as the buyers of the increased yield of water produced by weather modification. The problem of dealing with potential hold-outs among water producers organized only as individual proprietors would probably preclude effective marketing arrangements until such water producers were organized as some type of public enterprise capable of charging for water services without regard for the willing consent of each and every water producer.

Similar situations exist regarding the conduct of weather modification programs to alleviate storm damages. Large expanses of area in the western United States are under the jurisdiction either of the Bureau of Land Management in the U.S. Department of the Interior or of the Forest Service in the U.S. Department of Agriculture. Both agencies operate fire prevention programs in forest and watershed areas. Several large timber companies maintain similar programs on private forest lands and still other areas are organized as fire prevention districts with authority to tax local land owners for the operation of fire prevention programs.

Agencies operating fire prevention programs on timber lands or on watersheds provide the necessary institutional structures to be able to pay for weather modification programs to reduce fire losses produced by lightning strikes. Presumably such agencies would be prepared to contract for such services wherever a net savings could be demonstrated through the prevention of fire losses.

Still other opportunities may exist regarding potential savings in storm damage insurance as a justification for public expenditures to prevent storm damage associated with hail storms, wind damage, tornadoes, and hurricanes. Where such insurance is provided through private firms, a rating system might be used to calculate insurance risks with reference to the preventative actions being taken to reduce storm damages. Ordinary fire insurance is based upon such a rating system which takes account of publicly operated water-supply and firefighting facilities in establishing the price of fire insurance for each locality. Presumably additional expenditures for weather modification programs would be justified whenever such efforts would result in a net savings in the combined expenditures or outlay for storm prevention and storm insurance.

The same principle can also be applied to public insurance programs concerned with various forms of insurance against the loss of crops by storm damage. Potential savings realized in the costs of crop insurance payments would justify added expenditures for the prevention of storm damages.

Within the course of the last two decades a number of local government agencies have undertaken air pollution control programs. Those usually have been stimulated by public demand in areas where problems of air pollution have been the most aggravated. The experience which has been derived from these programs should be subject to careful evaluation. What alternative strategies have been used to control air pollution? What have been the results of these efforts? What are the economies of scale in the conduct of these programs? Do weather modification programs offer any opportunities to prevent atmospheric stagnation and the consequent diminution of the atmosphere's carrying capacity in the discharge of waste products? Answers to these questions would provide important increments to an expanding knowledge regarding the use of atmospheric resources based upon the experience derived from existing patterns of organizational arrangements.

The existing structure of institutional arrangements provides a basis for taking the first steps in the development of atmospheric resources. There are analogous problems in the development of common-pool or flow resources where the community of interests shared in the common property have reference to both private and public proprietary interests of diverse sorts. The basic concepts and methods used in solving those problems may prove to be useful tools for designing new solutiohs to problems in the development of atmospheric resources.

More than a century ago, pioneers advancing into the arid regions of the American West found it necessary to design and organize new institutional arrangements for the development of water resources. Some of their solutions were drawn from the concepts of mining law; some were drawn from the law of municipal corporations and adapted to the problems of human enterprise in a desert region. The institutional arrangements which form the contemporary structure of the California water industry were fashioned as incremental solutions to water problems over the course of more than a century of experience with life in a desert region. The deserts have been watered by human enterprise and the improbable prospect of a megalopolis in the desert has become a reality. We cannot foresee the future course of events in the development of atmospheric resources beyond a very limited time horizon. We can, however, anticipate some of the problems, analyze the appropriateness of existing concepts and methods for solving those problems.

What effects will decision-making arrangements in the American political system have upon the organization and regulation of a predominantly public enterprise-management system which does not function in an open competitive market economy?

Recourse is taken to public solutions and to the organization of public enterprises for the provision of public services where market solutions are not workable. As a result the self-regulating function of an open competitive market is not available for the regulation of public enterprise systems. Instead primary reliance must be placed upon public decision-making structures—legislatures, executive control agencies, courts, popular elections, etc. —to assume much of the burden for governing the conduct of enterprises functioning in the public sector of the political economy.

Some of the enterprise systems functioning in the public sector are the subject of continuing allegations regarding institutional failure and of persistent demands for radical reform. Public institutions for water resource management and for the provision of municipal or urban services generally are the most persistent subjects of attack and demands for reform. The allegation has been made that the so-called water crisis is a management crisis reflecting failures in the performance of the political system rather than being a crisis arising from the physical conditions of water supply. Similarly, municipal institutions concerned with urban problems have been the subject of sweeping allegations of institutional failure and of radical proposals for the fundamental reconstitution of the structure of American government.

As commitments are made to add new programs and new undertakings to requiring performance by institutions in the public sector we need to undertake a basic analysis of the structure, conduct and performance of public enterprise systems as they are regulated and governed by institutions of local, State, and the National Government. Basic research and analysis are the imperative problems, not that of prescribing solutions about what Congress *ought* to do. Knowledge about the political system, structure, conduct, and performance as an empirical system is quite as essential as knowledge about the atmospheric system before informed decisions can be taken about the consequences, risks, liabilities and exposures of undertaking special programs to attempt to control the atmosphere and to develop atmospheric resources.

To avoid some of the dangers of partisan and ideological biases entering into such studies, a self-conscious effort should be made to encourage independent investigation of the structure, conduct and performance of American government from many quite different approaches and with the use of different theoretical models. Much of contemporary political theory is based upon conceptions of political authority residing in a single center of power with a direct line of responsibility holding all governmental officials and employees responsible to that single center of power. This conception takes its inspiration from the parliamentary form of government and was effectively articulated in Woodrow Wilson's *Congressional Government*. In contradistinction to this linear approach to the conception of political authority would be the use of an equilibrium model as reflected in de Tocqueville's writing. The American political system in such a model is represented as having many independent centers of decisionmaking; and the conduct of government requires the maintenance of an equilibrium within the limits established by the veto positions exercised by these independent public authorities. The equilibrium model has a closer analogy to market structures and such a model offers prospects for devising self-governing or self-regulating mechanisms for balancing the relationships among many diverse enterprises operating in a highly differentiated public enterprise system responsive to diverse communities of interest ranging from the local community to the nation at large.

Appendix VII

HUMAN DIMENSIONS OF THE ATMOSPHERE FROM THE PERSPECTIVE OF A POLITICAL SCIENTIST

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Political scientists have taken little interest in the human use of the atmosphere or human reactions to atmospheric change. Generally, they have accepted the atmosphere as a "given," and have directed little thought to weather modification possibilities and the effects of such changes on human behavior. A few political scientists have studied the effects of weather conditions on election turnout. Some social scientists have discussed the relationship between weather and personality, usually without benefit of much evidence or acceptance of their findings by other scientists.

Political scientists, of course, have not ignored the relationship between technology in general and the political system. *The Scientific Estate,* a recent work by Don K. Price,[1] discusses the role of the scientist in political decision-making and the status of science in the policy process. Political scientists are certainly aware of the complex interplay between technological developments and social and political conditions, particularly as these affect strategy in international relations. They also recognize the political significance of technological breakthroughs in engineering and economic analysis, as shown in their extensive work on water resources. The insights gained from such policy-oriented studies can be valuable in examining the political and administrative aspects of weather modification. Weather modification will almost certainly involve some form of public control because of its political, economic, and strategic implications; and these and other problems deserve the interest and attention of political scientists.

Major Problems

The political and economic consequences of weather modification may require that regulatory mechanisms of several types be established. Some public agency may be needed to ascertain the professional qualifications of those engaging in weather modification. At the present time in California, for example, registration for weather modification activities does not involve a test of competence; it is simply a reporting statute. At another level, some public mechanism may be required to regulate payment of costs or to balance costs and benefits. If the Federal Aviation Administration undertakes fog suppression, should not those benefitted by service, notably the airlines, be required to support such services financially? If rainfall is induced in one location, may it not result in a long-time decline in precipitation in the downwind area, thus damaging the interests of those receiving less rain? What public mechanism can provide for balancing the benefits to those receiving the additional water with the costs to those receiving less? How will such a regulatory mechanism operate? How will technical, economic, and political factors be evaluated in deciding when, where, and to what extent to seed clouds?

Finally, weather modification has tremendous implications for public investment at all levels of government. Increased certainty with regard to water supplies may reduce the need and affect the design criteria for such major water installations as dams, levees, and urban storm drainage systems. Reduced spending for these facilities may then provide opportunities for increased investment in other areas. Such changes, however, will create new needs to re-examine and revise public policy.

Weather modification also has potential as a weapon in conflicts among nations. The ability to modify weather and to use this capacity to affect crops, river systems, and urban water supplies may give a nation strategic advantages. Weather control perhaps can also be used in more subtle ways to induce behavior changes over time. The many political and administrative implications of weather modification certainly require the attention of political scientists.

Research Needs

In their studies of public policy and decision-making processes, political scientists have used many approaches. These include traditional institutional analyses, case studies, inquiries into the attitudes and perceptions of decision-makers, and investigations of the relationships between given environmental conditions and policy outcomes. All of these techniques have produced useful insights and merit some discussion because of their possible application to weather modification problems.

Traditional institutional analysis examines the organization, procedures, and methods of handling public business. It is concerned with how efficiently an agency pursues its goals. It raises questions about the degree of competence required to make decisions, and investigates the roles of the legislature and bureaucracy. It deals with the more or less formal relationships among agencies having programs of common interest, and with methods for achieving coordination and cooperation.

Case studies are designed to clarify the dynamics of the political process through detailed accounts of the interplay of decisionmakers, policies, circumstances and available resources in resolving a given problem. While case studies have only limited value for purposes of generalization, they are useful in testing hypotheses, providing insights, and sharpening new theories about human behavior. Case studies demonstrate the evolutionary or incremental nature of problem-solving, and reveal, as perhaps no other research technique does, how time and changing circumstances affect the process.

Studies of decisionmakers' attitudes toward and perceptions of political phenomena have led to important concepts of role-playing in the decision process. Attitudes toward and perceptions of issues, political processes, other participants, and institutions have been shown to be related to individual background, status and seniority within an institution, levels and channels of communication, professional orientation and many other factors. Such studies have revealed many facts basic to bureaucratic or institutional controversy and have provided a firmer foundation for resolving such disputes.

Finally, political scientists have attempted to relate policy decisions to given conditions in the environment. Typical of such studies are those that examine the relationships of welfare policies to such varying political conditions as party competition, and apply statistical techniques to determine the significance of these relationships. Comparative studies across political cultures have been used to evaluate the persistence of such relationships.

All of these techniques are of potential value in examining and understanding human reactions to atmospheric change. Institutional studies, for example, would reveal some of the consequences of alternative methods of organizing regulatory programs in weather modification. Such studies would consider important administrative questions. What would be the advantages of establishing a new and independent government agency to regulate weather modification programs? What should be the formal and informal relationships between official weather modification programs and private groups concerned with such activities? How can sufficient protection be afforded both public and private interests? At what point is technical judgment required and at what point administrative judgment?

Case studies of decisionmaking in this field would provide some insights into the ways weather modification problems arise and how they are resolved. Such studies would reveal how various individuals and groups, both private and public, reach decisions about weather modification activities. At this time, little information of this type is available, partly because weather modification is a relatively new field. Several court cases have arisen over cloud seeding activities in various parts of the United States; these provide a very modest source of information about judicial behavior as it relates to weather modification. Much more needs to be learned about the behavior of legislators, bureaucrats and private parties in reaching decisions about weather modification activities.

Because the field is so new, little is known about attitudes toward weather modification and perceptions of such activities. As weather modification practices become more widespread, public notice will increase and more definable attitudes and views will emerge. Studies will then be needed to determine what these attitudes are. How much information do people have about weather modification? Do they want the weather to be manipulated? How do they feel about public control of weather modification activities?

Finally, as weather modification activities become more widely operational, it will be possible to study the effects of planned weather changes on individual and group behavior. If the snow pack is increased in a given area, what effect will this have on investments in ski areas and on individual decisions to ski? If water supplies are made more dependable, and destructive storms less likely, how will cities adjust their investment budgets and policies? What changes will farmers make in water management practices, types of crops grown, and soil erosion controls? How will public policy change when traditional programs (dams, irrigation systems) are no longer necessary? How will vacation patterns be affected by planned weather changes?

The political scientist will take great interest in how decisions related to weather modification activities are reached. Inevitably, multiple interests will be at stake in any weather modification program. How will these interests be protected in the decision-making process? How will decisionmakers operate within different time parameters? In short-term programs, decision needs will be apparent. In long-term programs, the effects will be felt only gradually; yet these effects will have to be anticipated and appropriate decision needs considered. Changing rainfall patterns will probably call for decisions related to the design and construction of dams, farm operations, forestry practices, storm drainage systems, recreational patterns, and numerous other social and economic activities.

Administrative efforts will be needed to protect the many interests affected by weather modification activities. Since most such activities will probably be carried out by private parties, the public function most likely will be regulatory. Should this regulatory function be performed by an administrative board on which multiple interests, both regional and economic, are represented? (Historically, such interest representation often has been more symbolic than effective in the regulator process.) Or should a single administrator or a line-type agency be responsible for regulating weather modification activities? In either case, how could the resources of the community be utilized most effectively? Would an advisory board provide adequate communication with the various interests involved? Would hearings of several types be useful for learning the varying viewpoints on issues of weather modification policy?

Should regional organizations be established to regulate weather modification activities? Regional organizations have been effective in water and power development programs, notably in the Tennessee Valley Authority. Since most weather modification programs will not be limited to state boundaries, it would seem that whatever public mechanism is established should transcend state jurisdiction, either on a regional or a national basis.

To what extent should public policy be established in statutory form? Should legislation dictate the areas in which cloud seeding may be carried on, or the types of storms that may be seeded? Should legislation dictate when and how tornado or hurricane control programs should be conducted?

What safeguards for community interests should be spelled out in legislation? What controls may be left to the experience and discretion of experts and administrators?

In some circumstances, decisions must be made with great speed, without consulting various interests. How can the community's interests be protected in these cases? Can contingency plans be devised which will guarantee protection of certain basic interests? What degree of discretion should be permitted in such situations? Can concepts from strategic defense planning be applied to uncertainties and contingencies in the weather modification field?

A regulatory agency should also concern itself with planning weather modification activities. In fact, perhaps the most important function of such an agency would be to inform itself of the most advanced techniques in weather modification and translate them into national, regional and local plans. The agency should also provide a channel for the distribution of research funds. Research itself could be carried on effectively through existing research organizations in the universities and private companies. But the regulatory agency, through grants to universities, would encourage interdisciplinary training for both physical and social scientists.

At this time, the major role of government at all levels probably should be to facilitate and promote research, rather than to impose strict limitations on the form, areas, or magnitude of weather modification projects. (The latter course might seriously inhibit the development of sophisticated concepts and technology.) At the present time, those engaged in weather modification activities could acquire insurance from private carriers, and this would probably provide sufficient community protection. At a later juncture, such insurance measures, however, might not be realistic or fully adequate.

The American public and American politicians have a high regard for scientists and technology. This admiration, however, should not lead those concerned with making policy decisions to think only in terms of technology. Weather modification proposals and plans should be considered by people who are also dealing with other kinds of policies which affect the quality of the environment. In this way, alternative strategies, some of which may not be technological in character, can be carefully examined and evaluated. Failure to consider non-technological adjustments to weather and climate may result not only in a great waste of resources, but also in unfortunate social consequences. Research in the social sciences should keep pace with developments in the physical sciences in order to avoid policies which promise technological progress without considering consequences to communities and individuals. Emphasis on technological solutions alone may lead to investments and practices that are uneconomic or undesirable in the long run.

The field of weather modification is in its infancy. Indeed, knowledge of the atmosphere is quite limited at this time. For this reason, it is premature to think in terms of definitive laws or policies which will protect all interests and insure an equitable distribution of benefits. We still must anticipate the effects and problems that weather modification programs may cause. We must create mechanisms to regulate activities and devise administrative and legislative means to handle problems. We must encourage research efforts and interdisciplinary cooperation. Then, as knowledge in the field advances, and as the consequences of weather modification activities become more obvious, adjustments in existing mechanisms and policies can be made.

FOOTNOTE

1. Don K. Price, *The Scientific Estate,* Harvard University Press, Cambridge, Mass., 1965.

Appendix VIII

WEATHER MODIFICATION AND LEGAL RESEARCH

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The purpose of this paper is to outline the state of existing legal research with regard to weather modification and to suggest areas where further research is needed. The paper is designed primarily for use by the National Science Foundation and other Government agencies concerned with research on legal problems raised by weather modification, as a means of assisting these agencies in deciding where to support research or where to undertake it themselves.

It should be noted that this paper is not intended as a comprehensive analysis of the relevant legal issues. Such an analysis would logically follow this writing, and would be many times more extensive than the present treatment. What is attempted here is a rough blocking out of those subjects which seem now to justify research initiative in view of the rapidly advancing technology in the field and the greatly increased interest in such activity throughout the Federal Government and elsewhere.

Major Questions

Set out below are the major questions that deserve early study in the field of law and law policy.

1. Study of existing Federal regulatory agencies to determine the relevance of their competence and experience to atmospheric control problems

It is widely agreed that certain aspects of atmospheric control should be subjected to Federal regulation. Little study has been made of whether this regulation should be undertaken by one of the existing Federal agencies or by a new one yet to be created. Exactly how such a regulatory body should be organized must still be settled. Several obvious analogies should be considered. The Federal Communications Commission, for example, does a type of geographical and atmospheric zoning in its control of radio frequencies, directional beam control, hours of operation, etc.; and the Federal Power Commission regulates various water and power systems throughout the Nation.

2. Study of the relevance of the Federal-review-board concept as expressed in the 1949 Hoover Commission Report and subsequent studies of Federal Government organization related to water projects

One of the important and immediate concerns raised by the prospect of weather modification is how the Federal Government should organize itself to control this activity. These organizational problems appear to be simliar to those raised in the water field involving coordination and review of agency programs. It would thus appear that the studies of the past twenty years of government organization in the water field might suggest desirable organizational precedents for the weather modification field.

3. Study of why and to what extent the Federal Government, rather than the States, should control human uses of the atmosphere

Various studies have urged that the Federal Government, rather than the State governments, should control man's use of the atmosphere, and especially weather modification. The advisability of Federal control seems obvious for certain large-scale weather modification activities, for example, regional climate modification. It is not so obvious for modification activities of smaller geographical scope and effect. A careful study of the various modification efforts affecting the atmosphere should be made to determine which are more appropriate for Federal and which are more appropriate for State control.

4. Study of why and to what extent the court-centered, common law system should control the human use of the atmosphere, and why and to what extent administrative agencies should exercise control

A number of factors limit the potential capacity of the courts to operate effectively in this field. Atmospheric changes often have a diffuse and subtle (albeit real) effect on particular individuals. In many cases very large areas and numbers of people will be involved; and changes in the atmosphere may pervade many aspects of life. Also, potentially catastrophic and irreversible effects may be brought about by man-made changes in the atmosphere. Finally, the cause-effect relationship between altered atmosphere and damage to individuals may often be impossible to prove. All of these factors may limit the ability of courts to deal effectively with problems raised by weather modification activities.

5. Why and to what extent the Federal Government should provide indemnity for damage caused by weather modification activities

Why and to what extent should this responsibility be borne by the private insurance sector? Several aspects of this problem ought to be considered. Should the Federal Government provide indemnity only for Federal agency activities? Is the Federal Tort Claims Act adequate to handle the new problems posed by weather modification? Should the Federal Government establish regulatory standards for the private insurance sector in its relationship to weather modification programs? Novel problems of indemnity appear to be posed by weather modification. Because this activity poses a high risk of very substantial damage, intensive studies are needed to examine the indemnity and insurance aspects associated with it.

Status of Research

The early interest in weather modification, primarily cloud seeding for increasing rainfall, reached a peak in the early 1950's. During this period, as much as 10 percent of the total area of the nation was subject to commercial cloud seeding operations; $3 to $5 million were expended annually by individuals, industries, and municipalities in the hope of economic benefits from this activity. Subsequently, because of much deflated expectations, commercial cloud seeding declined, In 1965, such commercial operations in the United States covered about 3 percent of the land area.[1]

Legal research has reflected this curve of general interest. Nearly all of the law review writing on the subject occurred in the 1950's. Except for certain Government-sponsored research, little interest has been shown by legal scholars in weather modification problems during the 1960's.

Several recent publications have provided good summary coverage of the various consequences of weather modification. One of the more comprehensive is found in a report to the U.S. Senate Committee on Commerce.[2] This report reviews the historical, scientific and legal aspects of weather modification. In a section covering the legal and legislative developments,[3] the report reviews the common law (nonstatutory) developments, the source of the Federal Government's power to regulate, existing legislation in the various States, litigation to date, possible tort law doctrines which might be used to recover damages, problems involved in Government (Federal and State) liability, and various issues arising out of possible Federal regulation.

A comprehensive report has also been published by the National Science Foundation.[4] This report presents information on the present status of scientific, biological, statistical, sociological, international, and legal aspects of the subject. It contains a summary discussion of potentially applicable legal theories (property law as well as tort law), past litigation, and suggested future action by the Federal Government. The "legal" section of this report is based in large part on a prior NSF report [5] of data obtained through a survey of the State and Federal agencies, research and experimental organizations, and commercial operators.

Two shorter articles together provide a summary discussion of a variety of legal issues. In the first,[6] Oppenheimer emphasizes questions of constitutional and administrative law: he gives a history of Federal and State legislation, and describes past litigation; he discusses legal theories and makes traditional legal analogies; and he offers recommendations for Federal action. (His discussion of State statutes and past litigation, however, is somewhat outdated.) In another article,[7] Oppenheimer deals with the activities of various Federal agencies in the area of weather modification, and with State legislation and the advisability of conducting Federal research projects in conformity with State statutes. He also discusses recovery of damages under the Federal Tort Claims Act and other Federal laws, and suggests lines of future Federal regulation.

Other publications of Government agencies provide information of varying degrees of significance to the legal researcher. The National Academy of Sciences and the National Research Council have prepared jointly a report [8] discussing various scientific and technical problems in this field. The section of the report dealing with the problems involved in the evaluation of weather modification projects [9] is of particular interest with respect to proof of cause and effect before a judicial or administrative body. A Department of Commerce publication [10] sets forth a proposed weather modification program to be followed by ESSA if this agency is given major responsibility in the field. This report is of technical rather than legal interest. The same may be said of a 1965 U.S. Congress report on proposed Federal Government actions,[11] which deals more with technology than with regulation. This publication considers policy only with respect to what actions the Federal Government should take and what agency or agencies should carry them out. The 1965 NSF Annual Report [12] describes the NSF reporting regulation proposed at that time. When that regulation, with a few changes, became effective on January 1, 1966,[13] that portion of the report lost its significance.

A University of Chicago publication [14] contains a number of excellent articles covering various social consequences of artificial weather modification. Two of these articles are of particular significance to the legal researcher. The first, by Edward A. Morris,[15] contains a summary discussion of litigation to date. The author points out that in this area law lags behind science, and that there is a need for further Government regulation and control. Of particular interest is the section regarding problems involved with hurricane control.[16] The second article, by Fremont Lyden and George A. Shipman,[17] presents the political scientist's view of possible governmental action relating to weather modification, and carefully analyzes each possible form of governmental regulation and control.

A number of law review articles deal variously with questions of governmental regulation, liability, and legal theories and analogies which might be used to support an action for damages.[18] In general, these articles may be said to be either too old in relation to present technology, or too bound up in traditional legal theory to be of real value for current weather modification activities and the problems they raise.

Finally, there are a number of student case notes on the two reported cases involving weather modification operations: *Slutsky v. City of New York*, 97 N. Y. S. 2d 238 (Sup. Ct. 1950); [19] and *Southwest Weather Research, Inc. v. Rounsaville*, 320 S. W. 2d 211 (Tex. Civ. App. 1958)

[*Southwest Weather Research, Inc. v. Duncan,* 319 S. W. 2d 940 (Tex. Civ. App. 1958)], *aff'd sub nom. Southwest Weather Research, Inc. v. Jones,* 327 S. W. 2d 417 (Tex. Sup. Ct. 1959).[20]

Future Directions for Research

What are some of the implications of this pattern of legal research? What further legal research is justified now which may not have been justified in 1950?

For one thing, the scientific community has learned much more about the feasibility and potential extent of weather modification activities. Until the mid-1960's a large and respectable segment of the scientific community was unconvinced that man had the knowledge and technical ability to modify the weather. Now there is wide agreement that weather can be modified in certain respects, although disagreement continues as to how much, where, and when such modifications can be made.[21]

Earlier legal research was concerned primarily with rainmaking. Now we are confronted with a much wider range of possibilities, including:

1. Rainmaking;
2. Hurricane modification;
3. Cold fog dispersal;
4. Warm fog dispersal;
5. Hail suppression;
6. Snow diversion;
7. Lightning suppression;
8. Regional climate modification;
9. More accurate weather prediction.

The differences in the nature of the legal problems raised by these various weather modification possibilities are substantial. Certainly the problems raised by cold fog dispersal over airports are vastly different from those raised by hurricane modification.

What areas of research justify further consideration by legal scholars? Some of the topics discussed below involve the more traditional approach of case analysis; some suggest a broader approach.

1. Opportunities and Problems for "Traditional" Legal Research

The "traditional" materials with which legal scholars work are appellate court decisions. This is possible because all State supreme court decisions, most lower State appellate court decisions, and all Federal appellate court decisions are printed and published in book form and are kept in numerous law libraries throughout the Nation. This type of research, however, has certain limitations. For example, even if one can accurately predict what the courts of one State will hold in a given situation, this does not necessarily tell much about what the State courts in the other 49 States, or the Federal courts, may decide in the same or similar situation.

To date, only a small handful of weather modification decisions have been rendered in all the State and Federal courts combined; thus, the traditional case law scholar must search further afield to find analogies in cases involving air and water pollution.

Traditional legal research has ordinarily been court-centered, i.e., it has been concerned with court-made law. Yet much of the law concerning weather modification will not be court-made law, and will not therefore fit into the traditional pattern. Later in this paper various suggestions will be made concerning noncourt law research. To the extent, however, that case law does have an impact on weather modification (and it obviously does), it needs to be examined more thoroughly than has been done to date.

Further research is appropriate on the legal issues raised by rainmaking. The technology of rainmaking has progressed considerably since the 1950's and the legal research of that period. Current research efforts, to be relevant to today's problems, must take into account recent technological developments. Needless to say, scholars doing legal research need to become well informed about the relevant technology.

2. "Reasonableness" in Nuisance and Riparian Rights Cases

The concept of "reasonableness" as expressed in the law of nuisance and the law of riparian rights should be thoroughly examined for possible applications to weather modification problems. A study of how the concept of "reasonableness" as expressed in the law of nuisance has been applied in cases involving use of the atmosphere for smoke disposal [22] would be useful. An examination of how "reasonableness" as expressed in the law of riparian rights has been applied in cases involving use of streams for waste disposal [23] would also provide valuable insights.

As yet the doctrine of nuisance has been explored only lightly for its possible applications to the use of the atmosphere for weather modification. For example, if A builds a factory on his land which casts smoke and fumes into the atmosphere, and these fumes are then carried across the land of B—A is making an intentional use of the atmosphere in somewhat the same manner as a weather modifier. He is using the atmosphere as a means of waste disposal, and in so doing he is imposing a cost on his neighbor B's land.

The similarity between the use of the atmosphere for waste discharge and for other "modifications" (e.g., cloud seeding) seems apparent. Both involve the use by individuals of an unowned but readily available natural resource. Both involve intentional modifications of that resource for the benefit of the modifier's own land. In both situations the conduct of the modifier is called into question only because it imposes some economic cost on another's land. Because of these similarities it would seem that a careful appraisal of the law of nuisance in smoke damage cases might be helpful in demonstrating how the courts are likely to treat weather modification problems in the future.

Similarly, the concept of "reasonableness" as applied in riparian rights law pertaining to waste disposal in rivers and streams can provide some interesting analogies. The law of riparian rights says that a man can use a river or stream flowing past his property for waste disposal so long as his use is "reasonable" in relation to the uses of others below him. There are some obvious similarities between this situation and that posed by weather modification. As with smoke nuisance cases, water pollution cases involve an intentional use of a readily available, unowned natural resource; and such use is called into question only when it causes damage to someone else.

3. Strict Liability, Trespass, and Negligence

Further research might also demonstrate the relevance (or lack of it) of various other legal theories to weather modification issues. Strict liability, for example, applies in cases of an activity considered "ultra-hazardous," i.e., an activity which "necessarily involves a risk of serious harm to the person, land, or chattels of others which cannot be eliminated by the exercise of the utmost care," and which "is not a matter of common usage." [24] Liability is imposed without regard to "fault," particularly in cases where the defendant's activity is unusual, involving abnormal danger to others, even though it is carried on with all possible precautions.[25]

Trespass [26] relates to the unauthorized entry of a person or thing upon land in the possession of another. Causing rain to fall on another's land (*Southwest Weather Research, Inc. v. Jones*) has been held to be a trespass. Flooding another's land has also been held to be a trespass. Casting smoke into the atmosphere which then is carried by the wind over another's land has sometimes been held to constitute a trespass, but usually not.

Negligence [27] is conduct which falls below the standard established by law for the protection of others against unreasonable risk of harm. For example, if cloud seeding is performed negligently, and no harm would have resulted except for that negligence, then liability may be imposed on the cloud seeder. Before this concept can be applied effectively, however, a standard for performance against which to measure the conduct of the weather modifier must be established.

4. Proof of Cause and Effect in Court Actions

One of the most critical questions in court actions for damages or injunctions resulting from weather modification concerns the proof of cause and effect. Before the courts award damages or injunctions for weather modification activities, they must be convinced, under rules long established, that (1) the modification attempt did in fact alter the weather; and (2) that as a result of this alteration the plaintiff was damaged (and would not have been damaged otherwise). Because of the nature of the weather modification problem, cause and effect will ordinarily be very difficult to prove. In the somewhat analogous situation of river pollution, it is often difficult, if not impossible, to prove which of many upstream users on a large river is causing the downstream user's damage. Similarly, it is often impossible to prove which of numerous industries is causing damage through air pollution.

It can be anticipated that many of the same difficulties of proof will be present in weather modification litigation. It will probably not be possible to prove that on a certain July 7, for example, one inch more rail fell than would have fallen but for the weather modification attempt, and that this additional rainfall was the cause of farmer Brown's damaged crops. At best, it may be possible to prove that over a given 6-month or 1-year period, 1 inch of rain was added to what normally would have fallen on a given area. This means that when the rainfall of an area is changed, certain benefits and costs will be shifted among the residents there; but the courts may be relatively powerless to allocate the costs so that they are also shared by those receiving the benefits. These problems and their implications should be given careful study.

5. The Role of the Courts and Federal Government in Weather Modification

The role of the courts in the field of weather modification is another difficult area requiring legal research. In the water field until 20 or 30 years ago, the courts provided one of the principal means of distributing the benefits of a business or activity among those who were damaged by it and who thus bore some of its costs. As society has become more complex, the court-centered system of water resource control has become inadequate to meet society's needs. These inadequacies of the court-centered system seem relevant to weather modification problems and might be summarized as follows:

A. Inability to handle the more sophisticated problems of cause and effect.

B. Inability to control the air or water polluter (or weather modifier) whose effect is so small on other users that these users find the expense of a lawsuit too great in relation to the recoverable damages. (Often the effect of one polluter on a stream or body of air is small and not in itself cause for concern; but many such effects, created by hundreds of thousands of polluters, may create a total effect which is substantial and perhaps disastrous to other users of the same resource.)

C. Inability to protect the public interest in a given condition of air, water, or weather.

D. Inability to develop uniform standards for resource quality.

E. Inability to develop long-range plans for development and use of water, air, and weather.

These inadequacies of the court-centered system have gradually brought about the creation of administrative agencies in various States and, now, at the Federal level. These agencies endeavor to carry out the functions that are either impossible or impractical for the courts to discharge. However, the role of the courts in weather modification activities is still an open one and should be carefully analyzed.

What is the role of the Federal Government in weather modification activities? What part can it play in the reallocation of costs and benefits connected with weather modification? One of the areas that needs study concerns potential insurance programs, and whether these should be under Federal or private control. One possibility is to leave such programs to private insurance companies, without Federal regulation. A second possibility is to leave the matter of insurance to private companies, but adopt Federal regulations defining the type of insurance required and possibly the rules which will determine when liability is to be imposed. A third alternative is to consider the creation of a Federally owned and operated insurance program. In considering these last two possibilities, some thought should be given to the question of rules or standards for proving cause and effect, and damage. Is it feasible, or desirable, to adopt different rules for proof in weather modification cases than are required for proof in ordinary civil lawsuits? Should rules in weather modification cases be more lenient toward the parties alleging injury or damage than in cases of normal civil action?

6. Decisionmaking for Hurricane Modification

The questions raised by the possibility of hurricane modification are in some ways unique. One very critical question relates to the decision-making function. What body should be responsible for decisions in the case of hurricane modification: existing Federal agencies, a new agency, Congress, the State Governments, or the President's office? It is quite possible that the social, political, and international implications of hurricane modification will be so enormous and spectacular that only the highest political decisionmaker in the country, i.e., the President's office, can take responsibility.

Hurricane modification also suggests other questions. How should indemnity questions be handled? Should the Federal Government compensate all persons damaged by an "altered" hurricane? Many other questions need to be raised and examined.

7. A New Approach for Legal Research

Still another factor, tangentially related to weather modification, should be taken into account: that is, the changing view of the nature of legal research from within the legal community itself. The recent report of the Committee on Research of the American Association of Law Schools is illustrative.

This report is critical of current and past legal research for being too concerned with what lawyers do with regard to the law rather than with the function of law in society. It points out, for example, that many persons in the legal-academic community think that "law is a function of the legal profession rather than a function of society." [28] The report suggests that more legal "research * * * should be aimed at exploring the problems that the community has in guiding its growth and in regularizing its relationships, and not simply the problems that lawyers encounter in participating in that process. Research in this frame of reference implies a disposition to take account of all potentially shaping forces in the development and regularizing process—social, economic, political, psychological and historical." [29]

Concerning the role of "traditional" research, the AALS report also notes that legal problems "are to a rapidly growing degree not case-to-case problems but rather those of complex administrative and economic systems and subsystems, for which case-oriented analysis is an approach of only incomplete relevance and effectiveness." [30] "If, on the other hand, 'law' is conceived as the processes, formal and informal, or regularization of social relationships through public intervention, the relevant universe of inquiry is greatly expanded." [31] Legal research should also take greater account of the "extent to which nonformal forces—such as economic cost, bureaucratic necessity, and social and political pressure—impose limits on the effectiveness of formal legal ordering." [32]

These admonitions apply especially to the field of weather modification, where, in all likelihood, lawyers as practitioners will play a relatively small role in the development of law. Yet there can be no doubt that law, more broadly conceived, will play a very important part in the field.

The National Science Foundation and other Government agencies might do well to encourage the type of broadly based legal research suggested by the AALS report with reference to weather modification. Certainly the returns from doctrinaire, case-oriented legal research in this field will be modest. This is not to say that such research is of no value: it has a distinct, but limited, value. A substantial amount of research should be devoted to the study of law as it relates to the social and economic goals posed by possible weather modification. What kinds of laws and what kinds of institutions might best be designed to achieve these goals? And what kinds of laws and institutions might best be designed to aid in the rational selection of goals?

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Appendix IX

THE INTERNATIONAL LAWYER AND WEATHER MODIFICATION

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This paper will suggest areas in which experts in international law and relations might be encouraged to make an early contribution to weather modification studies. A fair amount of attention has been given to domestic questions which weather modification activities raise; but so far the international implications have not received much notice. This lack is perhaps reasonable in view of the limited capabilities to make major changes which now exist; but it is unreasonable when we consider both the rate of technological change and the vast repercussions which a major ability to change weather would cause. A Soviet expert has just predicted the acquisition of such an ability within two decades.

For the future, we in the legal field may ask:

1. What are the questions lawyers ought to be asking themselves about the impact of weather modification activities and the need for legal direction and control?
2. What potential areas of international friction can be foreseen?
3. What mechanisms exist, or might be necessary, to prevent and resolve such disputes?
4. What efforts to date have posed and attempted to answer these questions?
5. What potentially are the most fruitful lines for future investigation and action?

Major Questions

The questions that lawyers should be posing for themselves fall into at least two major areas.

1. One set of questions depends upon understanding a pattern in weather modification activities and their probable physical consequences. Once a given weather change and its physical consequences are known, the lawyer can begin to think in terms of property, tort, and even contract; and he can begin to think of remedies available to those aggrieved. Can weather "belong" to a person, to a State of the Union, to a country? Are there rights in inchoate weather? If rights can be acquired, is it by capture, by first user?

Is weather like a river, an ocean, surface water, percolating water, underground water? What other analogies should be considered? Can a person "buy" someone else's weather? (He can certainly buy from another the results of weather, a stream, etc.) Assuming that "harm" (which may mean no more than "change") occurs, and that responsibility can be traced is the award of damages the "best" result—or is the best remedy prohibition of "harm" or "change"? Are there other remedies one could pursue? Should there be "immunities," or absolute liabilities, or some compromise restraints? Each course of action has social as well as legal effects.

2. Another set of questions relates to the role of the Federal and State Governments in weather modification activities. Should there be regulation? If so, by whom? What has been the experience under the almost two dozen State acts now in force? What is the Federal role? What have been the results so far under the Federal "rules" already in effect? How should Governments "control"—by license, by regulation, by tax, or by total prohibition? How can the Federal and State Governments best meet scientific, social and economic needs without conflicts among themselves?

No doubt other questions can be raised, but the foregoing list represents some basic questions with which lawyers can feel at home. For the most part, these are questions which have already been posed in the few domestic cases we have and in the literature to date. Setting priorities for solution depends to a great degree on what the physical scientists can tell us about the likely rate of development of weather modification technology.

3. In the international arena, many of the questions are the same. For example, even if there is firm international consensus that a state's weather modification activities must not cause harm to another state or its nationals, the standards as to what constitutes harm and liability are not thereby defined. Is a state's duty to "recompense" absolute, or is it based on some concept of wilfulness, or negligence, or what? How is recompense to be obtained, and before what agency or tribunal? How much duress is permitted?

Does a state "own" *its* weather? What weather has it a right to expect to receive? What measures can it take to protect itself agains deprivation or a change? Can another state obtain a "right" to experiment by offering compensation? If the losses are small, what arrangements exist or can be created to adjust them amicably? If they are large, will the same procedures work? If losses are major and threaten another country's survival, or its survival in comfort, what can be done? Is this a *causus belli?* What is the role of the United Nations Charter in regulating state action and reaction in this field? Does Article 51, which limits the use of force to a response to an "armed" attack, legally bar the use of force to prevent another country from destroying the weather *status quo?* The states of the Middle East have already argued that any interference with another state's water supply (a "result," after all, of weather) is itself "aggression" and will be resisted by armed force. Is this not rational in the context of desert economies?

Several international agencies already have an interest in meteorology, or at least in scientific pursuits. These include the World Meteorological Organization (WMO), the Committee on Outer Space Research (COSPAR), UNESCO, and others. What is their role now? What might it be as weather modification technology develops? Are other types of international agencies needed to consider special problems raised by weather activitities? If major weather modification becomes a reality, will it not change all international economic arrangements? If the deserts bloom, where and how will the crops be marketed, etc.?

Can existing international treaties serve as guides for weather modification activities? For example, do the bars to nuclear explosions established in the Antarctic Treaty of 1959 and the Test Ban Treaty of 1963 have implications for possible controls of weather modification activities? What treaty regimes (air law, international river controls, outer space provisions) offer useful precedents for dealing with potentially harmful experiments? From the history of these efforts, what can one conclude about the readiness of states to give up major potential advantages associated with weather modification activities?

Research Needs

Efforts to look at some of these questions, while not numerous, seem to have begun about a decade or so ago. A number of law review articles and Government publications, most of them quite recent, deal with some of these issues. The question of liability is touched upon in several newer studies of the problems caused by changing technology. The NSF's Special Commission has had a report prepared at Southern Methodist University on *Weather Modification: Laws, Controls, Operations.*[1] On the whole, only domestic questions have been raised by these various articles and studies, although the Special Commission's report notes some of the international political problems potentially involved. A 2-day meeting is planned at the SMU Law School in the fall of 1967 to survey the domestic legal problems and prospects raised by weather modification activities; and the State Department is beginning to look into the international law implications.

There is an obvious need for prompt consideration of the international aspects of weather modification activities before these become actual problems. The State Department (Office of the Legal Adviser) is already showing interest, as noted above, in the kinds of problems which we as a Nation and they as its international legal experts are likely to face as the technology of weather modification advances. There is also a need to study the international political-legal system to see in what ways it can adjust to possible changes caused by these technological advances. Proposed adjustments, of course, will be determined in part by how quickly we can expect wide-scale weather activities to become feasible. Several studies are now in progress concerning other aspects of technological change and domestic decisionmaking as these have bearing on international relations. Eugene Skolinkoff, for example, has just published *Science, Technology, and American Foreign Policy.*[2]

In many ways, the lawyer works best when he can see all the ground rules. In the field of weather modification, he needs to know the magnitude of prospective changes and whether or not they amount to "zero-sum" games. Historical experience makes one point clear: if we are certain to have "losers," we are certain to have complaints.

While a major project might be developed to study both domestic *and* international problems, there may be merit in handling research for the two areas separately. The rules emerging from study of domestic problems are likely to be different from those evolved for international issues; and the problem of enforcing agreed-upon rules is certain to be different for each area.

Many of the problems anticipated are interdisciplinary in their nature. The physical scientist's views on the magnitude and time-scale of potential changes are essential to further work. Political scientists—students of international relations—have much to offer. Economists also can help explore alternative techniques of accommodation and control.

If we look only at potential international problems, our machinery for decisionmaking ranges from primitive to nonexistent. It has always been difficult to achieve international solutions, at least where vital national interests and resources are at stake. There are, of course, some happier examples: the sharing of meteorological information thus far is one of them.

Clearly, one way of furthering mutual understanding among physical scientists, social scientists, practitioners, and administrators in a field is to have them talk to each other. This approach has accomplished much in the present project, as well as in such fields as atomic energy and outer space research. The need for interdisciplinary cooperation in studying the many implications of weather modification activities is indeed great. The domestic and international issues that are likely to be raised by major modification efforts deserve our early attention and every attempt to devise practical alternatives of accommodation and control.

FOOTNOTES

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Appendix X

MODELING PAPERS

PART 1—MEASURING THE ECONOMIC IMPACT OF WEATHER AND WEATHER MODIFICATION: A REVIEW OF TECHNIQUES OF ANALYSIS

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During the past few years there has been an increasing demand for improved techniques for measuring the impacts of weather and climate on economic activities. This demand stems in part from mounting losses of property and income which result from extreme weather events, in part from man's increasing use of the atmosphere as a transportation route, and in part from his increasing ability to modify the weather. Each year in the United States, for example, losses from tornadoes are estimated to be in excess of $250 million, losses from hurricanes in excess of $200 million, and those from floods over $290 million.[1] Large losses also result from lightning and hail—and from less extreme weather variations.

Part of these losses might be eliminated if improvements were made to existing weather information and forecasting systems.[2] Costly delays in air transportation which result from adverse weather might be reduced if better weather information were available or if weather could be altered.[3] Various other economic activities might also benefit from advances in the field of weather forecasting and modification.

Thus far, however, specific relationships between the weather and various economic activities have been explored only to a limited extent. Most of the research effort in this connection has been devoted to advancing knowledge about the impact of weather on agriculture,[4] and to a lesser extent on transportation [5] and the construction industry.[6] Little is known about the impact of weather on such economic activities as manufacturing or the service trades. Even in those activities in which a good deal of work has been done, knowledge of overall impacts is imperfect. In agriculture, for example, we have some indication of the effects of a particular weather variable on a particular crop in a particular region. But we still lack knowledge of how a given variable affects all crops in a given region, or of how each weather variable affects different crops in a given region. We can determine to some extent how a wet summer affects corn production in Iowa, but estimates of the overall impact on the Iowa economy are fairly crude. Estimates of impacts of particular weather events on the national economy border on guesswork.

Now that weather modification seems capable of achievement, it is imperative that much better estimates of the overall impact of weather on economic activity be obtained. Such estimates are needed because weather modification has differential effects on economic activities. Some activities may gain from a given weather change, but others may lose. Moreover, weather modification is but one of several possible adjustments to the weather. Estimates of overall weather impacts would be helpful in determining which alternative adjustment is most efficient. Would it be best to accept the weather as given and try to reschedule an activity (as in postponing planting or harvesting)—or try to insulate against weather effects (as in using air conditioning or drought-resistant crops)? Or would it be more efficient to try to alter the processes which produce the weather?

Possible Techniques of Analysis

One of the major topics of discussion at the Symposium on the Economic and Social Aspects of Weather Modification, held at the National Center for Atmospheric Research in 1965, was the problem of identifying and measuring the economic impacts of weather variations. Several tools of analysis which might be developed for this purpose were considered.[7]

Ackerman, for example, proposed the development of an Ideal Weather Model.[8] Such a model would identify and measure variations of actual weather conditions from conditions considered ideal for the pursuit of different economic activities, and would express the importance of these variations in economic terms. Development of such a model would require: (1) determination of the requirements of each activity for temperature, precipitation, and wind in terms of volume and timing; (2) assessment of the economic costs of variations in different weather parameters to particular economic activities; and (3) development of some means to trace the impact of a given weather variation through the economic system. Ackerman noted that considerable research is required before such a model can be applied. In particular, he emphasized the need to determine the weather requirements of various activities and the costs of weather changes to them. He suggested, however, that once these problems are solved, recent developments in applied economics, regional science, and computer science will facilitate the identification and measurement of weather impacts in various sectors of the economy.

The Symposium group considered several techniques that have been developed in recent years for analyzing economic systems, both at the regional level and national level. These techniques include: input-output analysis, simulation, linear programming, and regression analysis. In most cases to date, these tools have been applied without considering the climatic factors which may affect an economy: most econometric models have been based on the non-meteorological aspects of an economy. Even a casual look at the economy of most areas, however, reveals that climatic factors cannot be ignored. Hence, existing techniques for economic analysis must be assessed with caution. Generally, substantial modifications will be required before these techniques can be used for evaluating the real impacts of weather and climate on economic activities.

Input-Output Analysis

One technique that can be used to assess the real economic impacts of weather and climate is input-output analysis,[9] known also as interindustry economics. This method is concerned with quantitative analysis of the interdependence of producing and consuming units in a modern economy.[10] In particular, input-output analysis permits study of the interrelations among producers as buyers of each other's outputs, as users of scarce resources, and a sellers to final consumers. Once the linkages among various industries are known, it is possible to trace the impacts of a change in output of one industry on other industries in an economy.

A number of sophisticated models based on input-output concepts have been developed for analyzing economic changes in particular regions.[11] Attempts have also been made to develop a model of the United States economy using this technique.[12] However, most input-output studies do not take account of climatic factors.

Typical of non-climatic econometric models is the Arizona input-output model.[13] In considering the agricultural processing sector, this study shows that to produce a dollar's worth of agricultural products, it takes roughly 31 cents of input from the livestock sector, five cents of input from the crop sector, eight cents from trade and transportation, and so on. Inputs from rainfall, temperature, sunshine, wind, etc., however, are not considered.

Another study makes some attempt to assess the value of water to the Arizona economy.[14] For example, it reveals that of the 5.0 million acre-feet of water consumed in 1958, 1.5 million acre-feet were consumed by cotton, 1.4 million by food and feed grains, 1.3 million by forage crops, and so on. A subsequent analysis of these data indicates that the direct and indirect requirement to fill an order for an additional $1,000 of final demand varies from 65.0 acre-feet for the food and feed grains sector, to 0.03 acre-feet for the trade, transportation and services sector. The indirect economic effect of water is demonstrated in the poultry and eggs sector, which ranks 22d out of 24 in its direct water coefficient, but 3d out of 24 in its direct and indirect coefficient. It takes nearly 21 acre-feet of water usage in the State's agricultural industries to produce $1,000 of poultry products for the consumer. The explanation for the apparently high total is that poultry and eggs require large amounts of agricultural crop inputs, particularly food and feed grains, which are themselves large consumers of water. Here again the values of rainfall, temperature, and sunshine are not considered. If, however, these climatic factors were incorporated into econometric models of the type developed for Arizona, the impacts of changes in these weather parameters on the economy of a region could then be studied.

Variations in weather can obviously result in changes in the production functions of various activities. Given a change in the production function of one activity, input-output analysis can make it possible to determine the impacts of that change on other activities too. An increase of precipitation at a particular time, for example, may permit a significant increase in agricultural output. This in turn will increase the demand in the agricultural sector for inputs from other sectors. Increased output in the agricultural sector, however, does not necessarily imply that there will be increased outputs in all other sectors. Some economic activities may experience substantial gains, but others may suffer declines in the demand for their outputs. Input-output analysis therefore can provide a useful means of identifying which activities may gain and which may lose as a result of given weather variations.

Simulation

If it were possible to have a scale model of the economy, complete in every detail, one could alter one variable in the system and then observe what changes took place in other parts of it. Unfortunately, such scale models are not possible, partly because economic systems are not composed of physical mechanisms that can be scaled down, and partly because of the complexity of the systems. To overcome these problems, simulation models have been developed.[15] These use computer programs instead of physical models to represent the parts of the system and the interactions among the parts. Simulation models incorporate the variables that are believed to be the most important, and can then be used to determine the effects of a change in a particular variable on the system as a whole. The use of such models has increased considerably with advances in computer science and technology.

Simulation techniques offer useful possibilities for examining an economic system and the effects of weather and climate on its activities and on the system as a whole. One recent attempt to assess economic impacts of weather by simulation was made by McQuigg and Thompson.[16] They suggested that relations between weather events, non-weather events, man's function as a decisionmaker, and the economic outcome of an enterprise may be represented by an equation of the form

$$E=f(W,N,A)+u,$$

where E=economic outcome; $W=(w_1, w_2, \ldots, w_h)$, some actual weather events; $N=(n_1, n_2, \ldots, n_k)$, some actual non-weather events; $A=(a_1, a_2, \ldots, a_t)$, a subset of alternatives based on information supplied to the decisionmaker; and u=a "disturbance" factor, which is random and normally distributed.

Using this equation, a simulation model was developed, based on real economic data from an important weather-sensitive enterprise—the management of the flow of natural gas to a city during the winter. While the results of the simulation model analysis were being studied, a basic concept began to emerge: that improvements in the accuracy of weather information may allow the manager of a weather-sensitive process to make "better" and hence more valuable decisions, *provided he has a sufficiently precise rational method of translating weather information into operational terms.* It became apparent that the value of weather information and the use to which it is put depend on a much more detailed knowledge of weather impacts on weather-sensitive activities than is available at the present time.[17]

Simulation techniques may also be usefully applied to the evaluation of weather modification programs, which have characteristics similar to activities that have already been successfully subjected to analysis by simulation, such as transportation systems and environmental health. Simulation techniques for analyzing water resource programs,[18] particularly those which have evolved from the Harvard Water Program,[19] also show promise for applications to the analysis of weather modification programs.

Linear Programming

A relatively new contribution to the field of interindustry economics is the technique of activity analysis or linear programming, developed first by Dantzig and Koopmans.[20] Most applications of this technique have been to problems of single plants or firms, but the method itself is also useful for industry-wide and interindustry analysis.

Basically, activity analysis is a method of analyzing any economic transformation in terms of elementary units called activities. It provides the conceptual framework for the mathematical technique of linear programming, which can be used to determine optimum solutions to various kinds of allocation problems. This technique requires that the relationships among relevant variables be expressed in linear mathematical form. These expressions, together with appropriate constraints, make up a set of equations that have many solutions. The purpose of linear programming is to identify a particular combination of variables that will produce optimum results.

One example of linear programming is the PARM system. This programming model is built up of basic variables called activities, which are represented in the computation system by time-phased vectors grouped in tables. The maximum size of these tables is limited by the available computer memory, the prototype model having 983 such activity vectors. Wood suggests that regional applications would use a supplementary model adjoined to the national model.[21] Applying the regional model in any time period would assume prior application of the national model to that time period. The regional model, like the national model, would be applied first to the period immediately following the historical data, and then successively to subsequent periods, if desired. In this way the data computed for each time period would be added to the historical time series and used in the computation of the next period.

Regression Analysis

Regression analysis is also a valuable tool in many kinds of investigations, and particularly appropriate in studies of the effects of climatic variations on aspects of consumption and production. Until recently, multiple regression techniques could only be applied when the number of independent variables was relatively small. Today, however, with electronic computers, regression analyses with 10, 20, 30, or even more independent variables can be processed very quickly. Consequently, the "choice" of independent (climatic) variables is not as critical as it once was.

Regression techniques can usefully be applied to analyzing impacts of weather and climate on economic activities. For example, a regression model was recently developed to assess the effects of significant climatic variations on agricultural production in New Zealand, and their ultimate impacts on agricultural income.[22] With modifications, this model could be applied to the study of climatic impacts on agricultural production in other countries as well. Regression techniques could also be used to trace impacts of weather changes on other aspects of the economy.[23]

Potential Applications of Analytical Techniques

Thus far, applications of the various analytical techniques just described to the evaluation of weather impacts and weather modification programs have been more a matter of discussion than of accomplishment. Advantages and disadvantages of using these analytical tools for such evaluation have not been reviewed in detail. Neither has sufficient attention been given to the problem of what types of data or research are required before these techniques can be used successfully. Kuh, for example, states that "the quality of most available statistics is weak * * *. In many areas of research, computing capability and theory of estimation and behaviour have clearly outstripped the ability of our statistical agencies to produce pertinent data for testing and estimation, even though matters are constantly improving." [24] Clearly, research is needed to select useful data which can be expressed in quantifiable terms; to determine relationships between weather variations and weather-sensitive activities; and to direct imaginative efforts towards developing and adapting techniques for measuring impacts of weather and climate on various economic activities.

The papers which follow this introduction represent attempts to overcome some of the deficiencies in the field. Langford discusses in detail the possibilities of applying one particular technique, input-output analysis, to studies of economic impacts of weather and climate; and he notes the types of information that would be required for such efforts. He suggests that regional economic models, such as the one developed in the Philadelphia Region Input-Output Study, could be adapted to incorporate weather as a factor which influences the production functions of industries included in the input-output tables. He notes, however, that although it may be possible to use this method to determine impacts within a given region, substantial difficulties may be encountered in attempts to apply it for assessing inter-regional impacts.

In a second paper Hufschmidt, Fiering, and Sherwani discuss the possibilities of adapting water-resource system simulation models for use in measuring physical and economic impacts of weather forecasting and weather modification programs. Drawing on the experience gained in the Harvard Water Program, and noting the special problems raised by changes in natural streamflow patterns, they conclude that it would be possible to apply simulation techniques to the analysis of weather modification and weather forecasting programs. They note, however, that several sub-models would need to be developed for this purpose, including sub-models for providing information on streamflow-runoff relationships, flood probabilities, and the economic impacts of changes caused by alterations in normal weather patterns.

In a third paper, McQuigg describes a specific example of a simulation model that can be useful in studying economic impacts of weather modification. The physical process chosen for simulation was the deliberate creation of contrail cirrus clouds. To determine whether or not modification was needed, the simulation model used as basic input data the 20-year record of observed upper air temperatures in the area, together with records of daily maximum and minimum surface temperatures, precipitation, and percent possible sunshine. The model produced a useful modified series of temperature values, with components of variance that could be attributed to changes in the amount of cloudiness claimed. The modified temperature series provided reasonable estimates of the changes that could be expected if summer cirrus clouds over Missouri were modified by creation of a sufficient number of contrails. A natural extension of this work is to apply the model to simulation experiments involving the effects of temperature modification on electric power demand, dairy production, crop production, and other weather-sensitive activities.

The authors of these papers seem to agree that the various methods reviewed can be applied to the evaluation of weather modification programs. They point out, however, that in many cases, data must be gathered and research undertaken in order to improve the usefulness of analytical techniques. In particular, studies are required to determine the sensitivity of various economic activities to changes in different weather parameters. Studies are also needed to determine the ways in which weather information is used. What kinds of information tend to promote action to deal with weather events, and what types tend to promote no action? We need to know how people perceive the weather, and alternative adjustments to it. We need to know how much weather change is required before people will respond and whether reactions to planned changes differ from those to natural variations. At present our knowledge of these matters is quite limited. Further work is needed to develop and refine the conceptual bases of models for analyzing the economic merits of weather modification programs. Parallel work in empirical studies is also urgently required. Model building needs to be accompanied, for example, by studies of the weather requirements of various industries and regions, and by studies of the factors which seem to condition human responses to the weather.

FOOTNOTES

1. Environmental Science Services Administration, *A Proposed Nationwide Natural Disaster Warning System,* Washington, D.C., 1965, pp. 25–37.
2. See U.S. Committee on Government Operations, *Government Weather Programs,* U.S. Government Printing Office, Washington, D.C., 1965.
3. See W. Boynton Beckwith, "Impacts of Weather on the Airline Industry: The Value of Fog Dispersal Programs," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* University of Chicago, Department of Geography Research Series No. 105, Chicago, Ill., 1966, pp. 195–208; and U.S. Senate Committee on Commerce, *Weather Modification and Control,* U.S. Government Printing Office, Washington, D.C., 1966.
4. The literature on the impacts of weather on agriculture is voluminous. Recent contributions which review some of this work include John W. Kirkbride and Harry C. Trelogan, "Weather and Crop Production," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* University of Chicago, Department of Geography Research Series No. 100, Chicago, Ill., 1965, pp. 159–168. See also Emery N. Castle and Herbert Stoevener, "The Economic Evaluation of Weather Modification with Particular Reference to Agriculture," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* op. cit., pp. 141–158; Zvi Griliches, "Estimates of the Aggregate U.S. Farm Supply Function," *Journal of Farm Economics,* vol. 42, May 1960, pp. 282–293; Louis M. Thompson, *An Evaluation of Weather Factors in the Production of Corn,* Iowa State University Press, Ames, Iowa, 1962; and Earl O. Heady and J. L. Dillon, *Agricultural Production Functions,* Iowa State University Press, Ames, Iowa, 1961.
5. See, for example, E. Bollay and Associates, Inc., *Economic Impact of Weather Information on Aviation Operations,* final report to the Federal Aviation Agency, Washington, D.C., 1962; U.S. Weather Bureau, *A Preliminary Analysis of the Effects of Weather on Airport Traffic Flows, Airport Capacity and Acceptance Rates,* a report prepared by the Federal Aviation Agency, Washington, D.C., 1961; and E. J. Weigman, *Analysis of Wind and Weather Factors on the New York-London Air Route for Peak Traffic Day of August 22, 1962,* Stanford Research Institute, Menlo Park, Calif., 1962.
6. One excellent study is J. A. Russo et al., *The Operational and Economic Impact of Weather on the Construction Industry,* The Travelers Research Center, Inc., Hartford, Conn., 1965.
7. See, for example, Edward A. Ackerman, "Economic Analysis of Weather: An Ideal Weather Pattern Model"; W. L. Garrison, "Evaluation of Consequences of Modifications to Weather and Climate"; James R. Hibbs, "Evaluation of Weather and Climate by Socio-Economic Sensitivity Indices"; Ivars Gutmanis and Lester Goldner, "Evaluation of Benefit-Cost Analysis as Applied to Weather and Climate Modification"; Leslie Curry, "Seasonal Programming and Bayesian Assessment of Atmospheric Resources"; and Emery N. Castle and Herbert H. Stoevener, "The Economic Evaluation of Weather Modification with Particular Reference to Agriculture"—all in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* op. cit., pp. 61–76, 77–90, 91–110, 111–126, 127–140, and 141–158, respectively.

8. See Edward A. Ackerman, op. cit.
9. The technique of input-output analysis was conceived by Leontief. See W. W. Leontief, *The Structure of the American Economy*, Oxford University Press, Oxford, England, 1951. An excellent summary of concepts and applications of the technique appears in W. W. Leontief, "The Structure of Development," in *Technology and Economic Development*, Pelican Books, London, England, 1963, pp. 129–148. See also Walter Isard et al., *Methods of Regional Analysis*, John Wiley and Sons, Inc., New York, N.Y., 1960.
10. H. B. Chenery and P. G. Clark, *Interindustry Economics*, John Wiley and Sons, Inc., New York, N.Y., 1959.
11. See, for example, Walter Isard, Thomas W Langford, Jr., and Eliahu Romanoff, *Working Papers, Philadelphia Regional Input-Output Study*, Regional Science Research Institute, Philadelphia, Pennsylvania, December, 1966; F. T. Moore and J. Paterson, "Regional Analysis: An Inter-Industry Model of Utah," *Review of Economics and Statistics*, vol. 37, November 1955, pp. 368–383; and C. M. Tieart, *Markets for California Products*, California Development Agency, Sacramento, Calif., 1962.
12. See Gary Fromm and Lawrence R. Klein, "The New National Econometric Model: Its Application," *American Economic Review*, vol. 55, No. 2, May 1965, pp. 348–369. See also Morris R. Goldman et al., "The Inter-Industry Structure of the United States: A Report on the 1958 Input-Output Study," *Survey of Current Business*, U.S. Department of Commerce, Office of Business Economics, Washington, D.C., November 1964.
13. W. E. Martin and L. G. Bower, "Input-Output Analysis: An Arizona Model," *Arizona Review*, vol. 16, No. 2, February 1967, pp. 1–5.
14. W. E. Martin and L. G. Bower, "Patterns of Water Use in the Arizona Economy," *Arizona Review*, vol. 15, No. 12, 1966, pp. 1–6.
15. An excellent review of the concepts and applications of simulation techniques appears in Guy H. Orcutt, "Simulation of Economic Systems," *American Economic Review*, December 1960, pp. 893–907.
16. J. D. McQuigg and R. G. Thompson, "Economic Value of Improved Methods of Translating Weather Information into Operational Terms," *Monthly Weather Review*, vol. 94, 1966, pp. 83–87.
17. A similar point is made in J. A. Russo, "The Economic Impact of Weather on the Construction Industry of the United States," *Bulletin of the American Meteorological Society*, vol. 47, 1966, pp. 967–972.
18. Applications of simulation techniques in water-resource system design are described in Maynard M. Hufschmidt and Myron B. Fiering, *Simulation Techniques for Design of Water-Resource Systems*, Harvard University Press, Cambridge, Mass., 1966. See also Arthur Maass et al., *Design of Water Resource Systems*, Harvard University Press, Cambridge, Mass., 1962.
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22. W. J. Maunder, "The Effect of Climatic Variations on Some Aspects of Agricultural Production in New Zealand and an Assessment of their Significance on the National Agricultural Income," unpublished Ph. D. dissertation, University of Otago, New Zealand, 1965.

23. W. J. Maunder, "Effect of Significant Climatic Factors on Agricultural Production and Incomes: A New Zealand Example," *Monthly Weather Review*, vol. 96, 1968 (in press); "An Agroclimatological Model," *Science Record*, vol. 16, 1966, pp. 78–80; and "Climatic Variations and Agricultural Production in New Zealand," *New Zealand Geographer*, vol. 22, 1966, pp. 55–69.

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PART 2—A PROPOSED MODEL FOR THE EVALUATION OF ECONOMIC ASPECTS OF WEATHER MODIFICATION PROGRAMS FOR A SYSTEM OF REGIONS

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This paper proposes a model for identifying and evaluating some of the possible economic effects which might result from alternative programs of weather modification. While the economic implications of weather modification programs are only a part of the total impact upon society, economic analysis can provide valuable insights into many other areas of interest.

Four major criteria may be used in developing and evaluating the proposed model. These criteria are determined by the structure of the economy and by meteorological phenomena. First, the inputs and outputs of the model must be capable of being measured: all parameters, such as initial conditions, changes, and impacts, must be quantitatively specifiable. Second, the model should be sufficiently flexible, so that it can identify and represent the many complex relationships among the various parameters in both the economic and the meteorological systems. Third, the model should provide for spatial differentiation: weather is not uniform over all regions at a single time, nor is the impact of a single weather state uniform for regions having different structures. Fourth, the model should be capable of temporal differentiation: weather and economic activity occur over time, and any effects are clearly time-dependent.

Basic Input-Output Model

Prior reports have proposed input-output or inter-industry analysis as a viable construct to identify and quantify economic impacts of weather programs.[1] Inter-industry analysis has proven capable of representing the highly complex inter-relationships in rigorous form and of quantifying the effects of changes in the economic system in highly disaggregate form. The input-output model may be considered a social accounting system which measures the flows of current transactions through various sectors of the economy. In this accounting system, each sector or industry appears twice: once as a consumer or purchaser of inputs, and once again as a producer or seller of outputs.

Purchases of goods and services can be represented as a column vector, designated x_{ij}, where the subscript i indicates the industry producing the goods or services, and the subscript j indicates the purchasing industry. Thus, for all industries in an economy (1, 2, 3, . . . , *i*, *j*, . . . , *n*), an ($n \times n$) matrix array, x_{ij}, may be constructed. Figure 1 shows such a matrix.

The general framework of input-output relationships is derived from two basic equations. The first specifies that the total supply (output) of an industry, X_i, is equal to the total demand, where the total demand is the intermediate (structural) plus the final demand:

		PURCHASING INDUSTRIES								
		1	2	3	. . .	*j*	. . .	*n-1*	*n*
PRODUCING INDUSTRIES	1	X_{11}	X_{12}	X_{13}	. . .	X_{1j}	. . .	X_{1n-1}	X_{1n}
	2	X_{21}	X_{22}	X_{23}	. . .	X_{2j}	. . .	X_{2n-1}	X_{2n}
	3	X_{31}	X_{32}	X_{33}	. . .	X_{3j}	. . .	X_{3n-1}	X_{3n}
	.	.	.	.		.		.	.
	.	.	.	.		.		.	.
	.	.	.	.		.		.	.
	i	X_{i1}	X_{i2}	X_{i3}	. . .	X_{ij}	. . .	X_{in-1}	X_{in}
	.	.	.	.				.	.
	.	.	.	.		.		.	.
	.	.	.	.		.		.	.
	n-1	X_{n-11}	X_{n-12}	X_{n-13}	. . .	X_{n-1j}	. . .	X_{n-1n-1}	X_{n-1n}
	n	X_{n1}	X_{n2}	X_{n3}	. . .	X_{n}	. . .	X_{nn-1}	X_{nn}

Figure 1.—*General Input-Output Matrix*

$$X_i = \sum_{j=1}^{n} x_{ij} + Y_i,$$

where Y_i (final demand for product *i*) may be further described in terms of C_i (consumption) + I_i (investment) + G_i (government) + e_i (net exports). The second balance equation specifies that the total value of production (output) is equal to the total value of all inputs, *j*, where the total inputs are those purchased from other producing sectors (intermediate) plus the factor or primary inputs:

$$X_j = \sum_{i=1}^{n} x_{ij} + V_j,$$

where V_j (primary inputs to product *j*) may be further described as labor, capital costs, etc. (usually designated as "value-added").

The four basic assumptions of input-output analysis are surprisingly simple in their statement, but somewhat complex in their effect upon an empirical model.[2] First, the industries or sectors are defined such that the system is both mutually exclusive and exhaustive in its partitions. Furthermore, the sectors are homogeneous: that is, each commodity can be produced by one and only one industry; and each industry produces one and only one commodity. Secondly, it is assumed that a single linear production function exists for each commodity: that is, the inputs required by each industry are a function only of the level of output of that industry. Thirdly, additivity is assumed with regard to production functions: that is, the effect of carrying on several types of production is the simple sum of the separate effects. This excludes consideration of external economies or diseconomies. Finally, an assumption is generally made concerning the stability of production functions. This, in general, denies substitutability, relative price changes, and technological changes in production functions.

These assumptions constitute varying limitations, depending upon the specific characteristics of the input-output model constructed. For example, if a highly disaggregated sectoring system is used, the requirements of the first assumption regarding homogeneity can be reasonably satisfied; however, this may incur a corresponding decrease in the stability of the coefficients.

Modification of Industry Production Functions

A given industry may react to specific weather phenomena by modifying its production function—i.e., by purchasing different combinations of goods and services at the same or different prices, and/or by changing the level, composition, or price of its output. In terms of the input-output model, this is equivalent to substituting the production function

$[X_{ij}]'$ for $[X_{ij}]$.

$$\begin{bmatrix} X_{i1} \\ X_{i2} \\ X_{i3} \\ \cdot \\ \cdot \\ \cdot \\ X_{ij} \\ \cdot \\ \cdot \\ \cdot \\ X_{in} \end{bmatrix} \qquad \begin{bmatrix} X_{i1}' \\ X_{i2}' \\ X_{i3}' \\ \cdot \\ \cdot \\ \cdot \\ X_{ij}' \\ \cdot \\ \cdot \\ \cdot \\ X_{in}' \end{bmatrix}$$

Input-output analysis permits an extensive analysis of the impact of these changes, not only upon the industry modified, but also upon all other industries within the economy. In addition, input-output analysis permits an evaluation of the demand and supply for each resource; determination of whether the current availability of a given resource is a valid constraint upon the economic system; and if so, what the economic price of that resource may be, given the modified demands under specified conditions.

As an example, consider the effects of intermittent adverse weather conditions upon the construction industry. If an economic loss estimate of 1.76 per cent for the total construction business (developed by The Travelers Research Center, Inc.[3]) is assumed for the Philadelphia, Pennsylvania-New Jersey Standard Metropolitan Statistical Area, this loss estimate amounts to approximately $14,188,000. Using the Philadelphia Region Input-Output Table,[4] 89 industries would be affected by changes in the aggregate construction demand. These changes would range from approximately $53 for electric lamps to $2,158,542 for wages and salaries. Each of the 89 sectors would in turn change its demand, and the effect would spread with differential intensity throughout the economy.

The effect of the intermittent adverse weather conditions on an explicit production function was not examined to determine detailed probable expenditure changes. However, it is reasonable to believe that substantial changes would be observed in labor and in those industries producing protective equipment and perishable goods.

Inter-Regional Input-Output Model

An important modification to the basic model is to make it capable of spatial or inter-regional differentiation. With respect to weather, this is particularly important as modifications may not occur throughout the Nation, but rather to spatially differentiated segments of the economy. The impact of changes in a given region may be totally unlike those in any other region.

The modification to the basic input-output model is rather simple. Each producer and consumer is now differentiated by region, and the basic flows may be represented as in Figure 2. The two basic equalities previously discussed will hold when summed over all regions, that is:

$$\sum_{R=A}^{U} X_i^{RS} = \sum_{S=A}^{U} \sum_{j=1}^{n} X_{ij}^{RS} + \sum_{S=A}^{U} Y_j^{S}$$

and

$$\sum_{S=A}^{U} X_j^{RS} = \sum_{R=A}^{U} \sum_{i=1}^{n} X_{ij}^{RS} + \sum_{R=A}^{U} V_j^{R}$$

where commodities are denoted 1, 2, . . . , i, j, . . . , n; and regions are denoted A, B, . . . , R, S, . . . , U. Hence, where industries are spatially differentiated, the model describes the production function of each regional industry in terms of its inputs from all other industries. Similarly, the model presents the sales pattern to all industries over all regions.

A major limitation imposed by the addition of an interregional dimension to the model is the need to assume stability of spatial distribution patterns over time. However, it is still desirable to include such a modification in the proposed model because of the highly spatial effects of weather phenomena. Investigations are currently being conducted in regional input-output analysis to quantify regional effects. This spatial extension permits consideration

PRODUCING REGIONS AND INDUSTRIES		PURCHASING REGIONS AND INDUSTRIES: REGION A 1	2	3	. . . j	. . . n	REGION B 1	2	3	. . . j	. . . n	. . .	REGION U 1	2	3	. . . j	. . . n
REGION A	1	X^{AA}_{11}	X^{AA}_{12}	X^{AA}_{13}	X^{AA}_{1j}	X^{AA}_{1n}	X^{AB}_{11}	X^{AB}_{12}	X^{AB}_{13}	X^{AB}_{1j}	X^{AB}_{1n}	. . .	X^{AU}_{11}	X^{AU}_{12}	X^{AU}_{13}	X^{AU}_{1j}	X^{AU}_{1n}
	2	X^{AA}_{21}	X^{AA}_{22}	X^{AA}_{23}	X^{AA}_{2j}	X^{AA}_{2n}	X^{AB}_{21}	X^{AB}_{22}	X^{AB}_{23}	X^{AB}_{2j}	X^{AB}_{2n}	. . .	X^{AU}_{21}	X^{AU}_{22}	X^{AU}_{23}	X^{AU}_{2j}	X^{AU}_{2n}
	i	X^{AA}_{i1}	X^{AA}_{i2}	X^{AA}_{i3}	X^{AA}_{ij}	X^{AA}_{in}	X^{AB}_{i1}	X^{AB}_{i2}	X^{AB}_{i3}	X^{AB}_{ij}	X^{AB}_{in}	. . .	X^{AU}_{i1}	X^{AU}_{i2}	X^{AU}_{i3}	X^{AU}_{ij}	X^{AU}_{in}
	n	X^{AA}_{n1}	X^{AA}_{n2}	X^{AA}_{n3}	X^{AA}_{nj}	X^{AA}_{nn}	X^{AB}_{n1}	X^{AB}_{n2}	X^{AB}_{n3}	X^{AB}_{nj}	X^{AB}_{nn}	. . .	X^{AU}_{n1}	X^{AU}_{n2}	X^{AU}_{n3}	X^{AU}_{nj}	X^{AU}_{nn}
REGION B	1	.	.	.	.	.	X^{BB}_{11}	X^{BB}_{12}	X^{BB}_{13}	X^{BB}_{1j}	X^{BB}_{1n}	. . .	.	.	.	X^{BU}_{1j}	
	2	.	.	.	.	.	X^{BB}_{21}	X^{BB}_{22}	X^{BB}_{23}	X^{BB}_{2j}	X^{BB}_{2n}	. . .	.	.	.	X^{BU}_{2j}	.
	i	X^{BA}_{i1}	X^{BA}_{i2}	X^{BA}_{i3}	X^{BA}_{ij}	X^{BA}_{in}	X^{BB}_{i1}	X^{BB}_{i2}	X^{BB}_{i3}	X^{BB}_{ij}	X^{BB}_{in}	. . .	.	.	.	X^{BU}_{ij}	.
	n	.	.	.	.	.	X^{BB}_{n1}	X^{BB}_{n2}	X^{BB}_{n3}	X^{BB}_{nj}	X^{BB}_{nn}	. . .	.	.	.	X^{BU}_{nj}	.
. . .	. . .	.	.	.	.	.	.	.	.	.	.	. . .	.	.	.	.	.
REGION U	1	X^{UA}_{11}	X^{UA}_{12}	X^{UA}_{13}	X^{UA}_{1j}	X^{UA}_{1n}	.	.	.	X^{UB}_{1j}	.	. . .	X^{UU}_{11}	X^{UU}_{12}	X^{UU}_{13}	X^{UU}_{1j}	X^{UU}_{1n}
	2	X^{UA}_{21}	X^{UA}_{22}	X^{UA}_{23}	X^{UA}_{2j}	X^{UA}_{2n}	.	.	.	X^{UB}_{2j}	.	. . .	X^{UU}_{21}	X^{UU}_{22}	X^{UU}_{23}	X^{UU}_{2j}	X^{UU}_{2n}
	i	X^{UA}_{i1}	X^{UA}_{i2}	X^{UA}_{i3}	X^{UA}_{ij}	X^{UA}_{in}	.	.	.	X^{UB}_{ij}	.	. . .	X^{UU}_{i1}	X^{UU}_{i2}	X^{UU}_{i3}	X^{UU}_{ij}	X^{UU}_{in}
	n	X^{UA}_{n1}	X^{UA}_{n2}	X^{UA}_{n3}	X^{UA}_{nj}	X^{UA}_{nn}	.	.	.	X^{UB}_{nj}	.	. . .	X^{UU}_{n1}	X^{UU}_{n2}	X^{UU}_{n3}	X^{UU}_{nj}	X^{UU}_{nn}

Figure 2.—*Regional Input-Output Matrix*

of the impacts upon industries in region S resulting from a weather modification in region R because of the economic interdependence of regions.

Interregional Weather Modification Matrix

The obvious extension is to include interregional weather relationships within the theoretical construct. Having first analyzed spatially the economic effects of weather modifications in region R upon the economic system in that and all other regions—with the weather in all other regions constant—the effects of the weather modifications in region R upon the weather in all other regions can now be considered. This interrelationship of weather states can be represented by a transitional probability matrix. The conditional probability in any cell of the matrix is described in this way: given the modification in region R from weather state γ to weather state δ, the weather in region S will be modified from state η to state ζ (where possible weather states $\alpha, \ldots, \gamma, \ldots, \delta, \ldots, \eta, \ldots, \zeta, \ldots, \varpi$ exist in each of A, B, . . . , R, S, . . . , U regions). This probability is represented as:

$$P^{R_{\gamma}}_{S_{\eta}}$$

The following probability definitions are determined:

$$0 \leq P^{R_{\gamma\delta}}_{S_{\eta\zeta}} \leq 1$$

and

$$\sum P^{R_{\gamma\delta}}_{S_{\eta\xi}} = 1$$

The transitional probability matrix may be related to the modified production functions introduced earlier so that the production functions

$$\begin{bmatrix} \cdot \\ \cdot \\ \cdot \\ X^{RS}_{ij} \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \quad \begin{bmatrix} \cdot \\ \cdot \\ \cdot \\ X^{RS'}_{ij} \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \quad \begin{bmatrix} \cdot \\ \cdot \\ \cdot \\ X^{RS''}_{ij} \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \quad \cdots$$

are described as functions of the weather states in the producing region, that is:

$$[X^{RS}_{ij}] = \int(\text{Weather state in region R})$$

Here, it is important to note that the operational value of the system may depend in no small degree upon the definitions of the weather states. Initially, the weather states can be described in terms of observable and quantifiable parameters, the discrete states so defined as to include maximum variation in production functions between weather states and minimum variation within each state. Hence, the description of the weather states is operationally made a function of the modifications in production functions. However, attaining a set of weather states which are consistent with possible modification programs and meteorological observations may be a major problem.

It is clear that while the proposed model is theoretically appealing, it has many empirical shortcomings given the current state-of-the-art. At present, two major gaps exist. First, information relating to the specific changes in production functions is lacking. Detailed studies are needed to determine precisely what these modifications are.[5] Initially, it may be possible to use the highly explicit linear functions, developed in detailed inter-industry studies, and to base modifications on ideal as well as probable engineering or technological changes. However, detailed empirical studies of specific changes in production functions are required.

Second, the temporal and spatial inter-relationships of weather states (both initial and modified) have not been sufficiently determined to permit development of the probabilistic segment of the proposed model. Research should be undertaken to determine the effects of weather modifications, if any, upon the "normal" weather system.

If these two major gaps can be bridged, the proposed model can be made workable. A number of input-output models do exist for specific regions, although these are not entirely comparable. Researchers are continuing to examine methods by which characteristics of the physical environment may be included within input-output models. For example, some work with the hydrological cycle has already been included in a study of the Colorado River Basin.[6] The Philadelphia regional study is to be expanded to include the Delaware River Basin model, so that water quality policies can be related to regional economic activity.[7] The work in developing a basic input-output model for evaluating economic aspects of weather modification programs has been a challenging and expensive task. There is a growing belief among some regional economists that with modifications to basic parameters, such a highly detailed model can be adapted successfully to various regions at relatively low cost.[8]

FOOTNOTES

1. See Edward A. Ackerman, "Design Study for Economic Analysis of Weather Modification," in Advisory Committee on Weather Control, *Final Report*, vol. II, U.S. Government Printing Office, Washington, D.C., 1958, pp. 235–245.
2. A voluminous literature has been developed concerning related theoretical and mathematical implications of input-output structures. For a detailed discussion of these, the reader is referred to the following: Wassily W. Leontief, *The Structure of the American Economy, 1919–1939*, 2d Ed., Oxford University Press, N.Y., 1951; W. W. Leontief et al., *Studies in the Structure of the American Economy*, Oxford University Press, N.Y., 1953; Hollis B. Chenery and Paul G. Clark, *Interindustry Economics*, John Wiley and Sons, Inc., N.Y., 1959; Walter Isard et al., *Methods of Regional Analysis*, Technology Press and John Wiley and Sons, Inc., N.Y., 1960; Richard Stone, *Input-Output and National Accounts*, Organization of European Economic Cooperation, Paris, 1961; National Bureau of Economic Research, *Input-Output Analysis: An Appraisal*, Studies in Income and Wealth, vol. 18, Princeton University Press, Princeton, N.J., 1955.

3. J. A. Russo, K. Trouern-Trend, R. H. Ellis, R. C. Koch, G. M. Howe, G. H. Milly, and I. Enger, "The Operational and Economic Impact of Weather on the Construction Industry of the United States," The Travelers Research Center, Inc., Hartford, Conn., March 1965, pp. 55–74.
4. Walter Isard, Thomas W. Langford, Jr., and Eliahu Romanoff, *Working Papers: Philadelphia Regional Input-Output Study,* Regional Science Research Institute, Philadelphia, Pa., December 1966.
5. See the recommendations in the *Final Report* of the Task Group on Human Dimensions of the Atmosphere concerning this research need.
6. Bernard Udis and Gilbert W. Bonem, "Water Use and the Colorado River Input-Output Study," University of Colorado, Boulder, Colo., January 1966.
7. Economics of Water Quality for a Regional System, undertaken by Regional Science Research Institute, Philadelphia, Pa., under Public Health Service Research Grant WP–00938–01.
8. Isard, Langford, Romanoff, op. cit.

PART 3—SIMULATION MODELS FOR WATER-RESOURCE SYSTEMS: THEIR UTILITY IN MEASURING PHYSICAL AND ECONOMIC EFFECTS OF WEATHER FORECASTING AND WEATHER MODIFICATION: SUMMARY REPORT

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Purpose and Scope of Report

The purpose of this report is to examine the feasibility of adapting water-resource system simulation techniques, as developed in the research of the Harvard Water Program, as a means for testing the physical and economic effects of weather management and forecasting on controlled water-resource systems. Existing simulation and hydrologic synthesis techniques, as reported in the literature, are examined to determine the additions and changes that would be required to adapt the models and computer programs to this purpose. No new models are developed nor simulation programs written. Rather, the report is limited to an examination of the "state-of-the-art" in simulation and hydrologic synthesis as it relates to weather modification and forecasting problems, and a statement of further research required to adapt these techniques in order to deal effectively with such problems.

Role of Simulation in Water-Resource Planning and Decisionmaking

The term "simulation" has no precise definition which is commonly accepted by operations researchers and systems analysts. In very general terms, simulation can be described as a process which reproduces the essential elements of a system or activity without attaining reality itself. In the spectrum of systems analysis methods, ranging from the most to the least abstract, simulation occupies the middle range.

Simulation can be used both in the construction of didactic or teaching models and as an aid in design and planning processes. Simulation can consider microscopic as well as macroscopic phenomena. One may be interested, for example, in simulating a path taken by a particle (e.g., a charged atomic particle or a molecule of water), subjected to certain driving forces and constrained by certain boundary conditions. If decisions at the several branches of a network consisting of all such paths are resolved on a probabilistic basis, simulation is a particularly powerful tool for deriving the statistical characteristics of the behavior of a group of particles. Then, by comparing predicted to observed behavior, it is often possible to verify (or reject) hypotheses concerning the fundamental causal structure of the phenomenon under investigation. In such a case, the simulation model is said to be didactic because it attempts to teach or explain a natural phenomenon in terms of concepts which can be represented adequately by a series of symbolic relationships. This approach is akin to the solution of partial differential equations by Monte Carlo techniques, a subject on which there is abundant literature.

Simulation takes on quite a different character when it is used as an aid in the design process, wherein we typically deal with large and complicated systems. The components of such systems, symbolized by *decision variables* to which particular numeric values are attached, are logically or physically interconnected to form a network. The network receives *inputs* (information, energy, or materials) and processes them to yield *outputs* (policies, allocations, or commodities). We wish to specify some *optimal* set of decision variables, one which obeys the relevant constraints on system performance and elicits the best possible response or set of outputs. This implies the existence of a means for measuring system response or performance in terms of a set of goals or objectives expressed formally as an *objective function,* whose value is to be maximized or minimized. Where objectives are expressed in economic terms, the formalism for measurement is called the *benefit function;* the function to be maximized in this case is the value of gross economic benefits less economic costs or losses.

Simple design problems of this form may be "solved" (in the sense of obtaining an optimal design) analytically and exactly. However, most realistic problems of resource allocation, including water-resource design problems, involve so many social, economic and technologic factors in so complex an interplay that it is necessary to resort to simulation for approximate solutions to the optimization problem.

Structure of a Simulation Program

A digital computer simulation program for a water-resource system would have the following major segments:

1. A set of subroutines to handle the physical laws governing system operations. For example, in simulating the operation of a water storage reservoir, the law of conservation of mass must be obeyed: that is, the quantity of water in storage at the end of some time interval (day, week, month, or year) must equal the initial storage plus the inflow less the outflow (which includes reservoir releases, diversions, evaporation and seepage).

2. A set of subroutines to assure physical consistency. For example,

the quantity of water in storage must neither become negative nor exceed the storage capacity of the reservoir.

3. A set of subroutines to make the essential logical decisions based on a predetermined or flexible system operating policy. For example, these subroutines would make allocations from available water sources to serve competitive alternative uses for those sources. It might be necessary to decide which of several alternative water uses receives water, or from which of several alternative storages a unit of water is supplied to meet some downstream demand.

4. A set of subroutines to evaluate the economic consequences of the vector of system outputs associated with a decision or set of decision rules. In a water-resource system, this involves calculating (i) the gross benefits associated with each system output, (ii) the capital, operation, maintenance, and replacement costs associated with system inputs, and (iii) the discounted values of net benefits for the system.

5. A group of subroutines to monitor the input-output process. These subroutines tabulate the output in compact and orderly fashion, assign and print appropriate headings, read cards and tape as prescribed in the program, and exercise the several input-output options that are generally included in a major simulation effort.

6. A group of subroutines to handle the input data, including the values of *exogenous* variables, used by the simulation program. These include administrative or program control data, trial values of design and operating policy variables (reservoir sizes, allocation of reservoir capacity to specific uses, parameters of economic cost, benefit and loss functions), and exogenous variables associated with natural events or processes.

Streamflows are important exogenous variables in all water-resource systems. In design of a sophisticated water-resource system, we may also be concerned with groundwater levels, precipitation, evapotranspiration, soil moisture levels, and other meteorological phenomena.

Streamflow data may be in the form of an historic record. An alternative set of data can be produced by a recursive model which utilizes the statistical characteristics of the short historic record to define the statistical properties of the runoff process and then iterates through a stochastic process to generate long synthetic traces of streamflow. A model of this type preserves the relevant moments (mean, standard deviation, correlation, etc.) of the flow regime, the basic assumption being that the observed hydrologic record is a sample from a stationary stochastic process. The purpose of simulating streamflow is to obtain alternative sample traces which may reveal the flow sequences that are as likely to occur in the future as is the observed sequence. This is particularly useful in design because relatively minor changes in the sequence of recorded streamflows can have major influence on the results obtained.

7. A set of subroutines to serve as executive control of the entire program and of the calling sequences for the several subprograms.

Operation of the Simulation Program

Simulating the behavior of the system proceeds (1) by assigning initial trial values to the decision variables (size of reservoirs, power plants, aqueducts; allocations of reservoir capacity to uses; output requirements for water supply, energy, etc.); (2) by operating the selected system over a selected period of time, using the exogenous variables; and (3) by observing the physical and economic response of the selected system. In effect, water is routed through the system according to the rules of the operating policy.

The use of simulation in the design process proceeds by selecting other combinations of decision variables and operating the system for each trial combination. The responses associated with the trial decisions are then ranked in terms of the adopted measure of response—typically, net economic benefits.

In all but the simplest systems, the number of designs which are significantly different in terms of the values of decision variables is astronomically large. Therefore, only a small sample of all such possible combinations of design variables can be tested with reasonable expenditure of computer time. The means by which such sampling can best be done comprise a considerable body of research, involving random and systematic sampling techniques and various optimum-seeking methods. Sampling and search techniques are not discussed in this report, but appropriate references to the relevant literature on this subject (and others discussed in this paper) can be found in the bibliography which appears in the basic report of which this is a summary.

Adapting the River-System Simulation Model To Handle Effects of Weather Phenomena

The simulation program outlined in the preceding section of this report accepts streamflow as an input. However, it contains no model or subroutine for deriving streamflows from precipitation records. The system operating policy is not specifically adapted to handle streamflow forecasts with varying degrees of reliability. Furthermore, the benefit evaluation subroutines are not designed to assess effectively the gains obtained from forecasting and weather modification.

In order to adapt a simulation program of the type described above so that it can handle weather modification and forecasting situations, the following additions and changes are required:

1. Exogenous data: essentially the historic precipitation and climatologic record.

2. Synthetic precipitation generator, using historic precipitation records as inputs.

3. New exogenous data: information on the nature of modifications of precipitation (supplied by meteorologists concerned with the weather modification problem to be examined).

4. Precipitation-runoff model, translating precipitation data into runoff data.

5. Streamflow-forecast model.

6. Revised operating policy model, adapted to handle streamflow.

7. Revised economic evaluation sub-model, adapted to handle deficits under conditions of natural and modified precipitation, and conditions of streamflow forecasting and absence of forecasting.

In most cases, it will be necessary to develop completely new models of the kinds listed above. (These are discussed in greater detail in the following section.) The structure of the Lehigh-type water-resource simulation program can accommodate such revisions and additions. However, it will probably be necessary to make substantial revisions in this simulation program in order to obtain an over-all model which can readily accommodate weather modification and forecasting parameters and variables.

System Subroutines

The system subroutines required to adapt existing water-resource simulation programs to deal effectively with weather modification and forecasting can be classified as follows:

1. Subroutines dealing with precipitation and with precipitation-runoff relationships. These include the synthetic precipitation generator, and the precipitation-runoff and streamflow-forecast sub-models.

2. Subroutines dealing with operation of the water-resource system, given the information provided by the precipitation and runoff subroutines. These include the flood-flow, low-flow, and general operating policy subroutines.

3. Sub-models assessing the economic effects of system operation, using the subroutines of 1 and 2 above.

Synthetic Precipitation Generator

If simulation analyses are not to be restricted to the relatively brief time-span of the historic precipitation record, some means must be found to synthesize long traces of precipitation data. Precipitation records are generally longer than streamflow records, and the moments of precipitation distributions tend to be better defined than those of their flow counterparts. In addition, precipitation records, more so than flow records, are subject to periodic or spectral analysis, from which trends and cycles may be more readily identified. On the other hand, precipitation records are temporally and spatially much more variable than corresponding flow records, primarily because flows represent an integration effect over relatively large areas and are less influenced by local climatological perturbations and irregularities.

Several procedures have been used for the synthesis of rainfall sequences.

Annual rainfall depths frequently show little or no persistence or serial correlation; accordingly, sequences of annual rainfall can be generated through random sampling. Time intervals short enough for use in small drainage basins or in forecasting models (e.g., hours) present several problems. For such short time periods, it has been shown that single-lag Markov models and linear autoregressive schemes fail to reproduce the characteristics of the historic record. Generation of rainfall series by using probability distributions for storm durations and the intervals between such storms, by the number of runs of given length, and by the modification of some well known probability distributions has been successful to varying degrees. Another approach involves application of multivariable, multilag models which consider antecedent, current, and forecast precipitation records, and use of other weather data which will become available from weather satellites. Although promising beginnings have been made in developing and testing such approaches and models, much further research is required before we will be able to generate synthetic traces of precipitation which meet the required tests of adequacy and reliability.

Precipitation-Runoff Models

Much work has been and is being done to develop reliable procedures for predicting runoff from precipitation and other meteorological phenomena. The problem is difficult because the physiographic features of a natural watershed which affect runoff vary within wide limits, even within a single watershed, and give rise to pronounced differences in response. Engineers, hydrologists, and soil scientists have evolved special techniques to suit their particular data and problems. Many of these formulations are remarkably ingenious. Included among the independent variables are measures of orographic features, stream bifurcation, hydraulic slope, vegetative cover, land use, farming practice, thunderstorm frequency, storm duration, snow pack, thermal gradient, lapse rate, antecedent precipitation and soil moisture. However, there appears to be no general analytical approach which is equally applicable under diverse climatological and hydrologic regimes. This arises because the combined effects of climatic pattern, vegetation, topography, and soil profiles on runoff pattern are not clear.

The lack of a general analytical approach has led to a search for methods and models weighted heavily toward the empirical. Most of these fall into one or more of the following classes:

1. Empirical methods.
   a. Rational formulae.
   b. Regression and correlation models.
   c. Unit graph methods.
      (1) Graphical.
      (2) "Black box" models.
2. Analytical routing techniques.
3. Moisture accounting procedures.

a. Evaportranspiration.
b. Multi-level models.
c. Multi-capacity models.
d. Multi-lag filter models.

4. Component models.

Basically, the empirical methods fit curves to actual observations of rainfall, runoff and characteristics of drainage areas. The precise form of the fuctional relationship between rainfall and runoff—logarithmic, exponential, polynomial or other form—depends upon the combination of characteristics unique to the watershed. No single functional form is equally applicable to all water regimes.

A basic criticism of the regression and correlation models is that the so-called independent variables are not necessarily independent at all. Thus, while least-squares or other appropriate curve-fitting techniques may produce excellent agreement with the observations, the fitted function may be totally inapplicable outside the range of observation, and some extreme combinations of independent variables may produce estimates of runoff with extremely high sampling variances.

The development of unit hydrograph procedures has progressed from Sherman's graphical method to the present-day conceptual models of instantaneous unit hydrographs. Modern expositions of unit hydrograph theory treat the watershed as a "black box" which operates on rainfall input to produce runoff. The most common model applied to catchment behavior is that of a linear, time-invariant, lumped system. There is no explicit consideration of topography, geology, soils, vegetation, or the areal distribution of rainfall; time is the only independent variable. Some distributed linear models have been proposed, but they are too complicated for general application. A valuable advance would be made if physical significance could be imputed to the parameters of the new models. Extension of the models to take account of areal variability of rainfall would be a decided advantage.

There is considerable evidence that the rainfall-runoff process is nonlinear. The unit hydrograph is not a fixed property of the watershed; rather, the response varies with the intensity of rainfall. New analytical techniques are needed to handle variable watershed response. This is now possible only for very simple rainfall distributions.

The routing model of a basin system is used to transform the rainfall excess to direct runoff. The problem of modeling overland flow and routing in streams can be approached analytically. The only rigorous methods for simulating unsteady flows are the finite difference techniques for the numerical solution of the governing partial differential equations. The basic nature of overland flow is not well established. The formidable data requirements and computing techniques are the major obstacles to use of these methods. The accuracy to be obtained by use of these techniques is also open to question because of the limited accuracy of the basic data.

Recently, digital models with discrete component subsystems have been developed to simulate the overall catchment behavior in physical terms. The Stanford Watershed Model developed by Crawford and Linsley belongs to this category. The land phase of the hydrologic cycle is represented by a network of interrelated storage elements. The individual storages are depleted and refilled deterministically according to the physical processes involved. The model is programmed to use 15-minute or hourly rainfall, daily potential evapotranspiration and a number of physical parameters characterizing the watershed. From these data, continuous actual evapotranspiration, infiltration, overland flow, interflow, and groundwater outflow are found. Provision is made for routing overland flow with additions from interflow and groundwater flow components to obtain hourly runoff values.

Since the statistical treatment of the model parameters (which are neither independent nor mutually exclusive) is unreliable, a functional relationship must be established for each flow component. The behavior of components is approximated by empirical relationships. Estimates of the parameters that fit the general model to the given catchment are obtained from rainfall and runoff records for the catchment, covering a 5- to 6-year period. Initial values of some model parameters are selected on the basis of experience and judgment. A second period of record is used as a control, to check the suitability of the parameters obtained from the first period. The parameters are adjusted until anticipated responses, within an acceptable tolerance, are achieved from known inputs.

The Stanford Model requires a substantial amount of data and computing time to produce a suitable set of coefficients. It uses a combination of heuristic and algorithmic approaches. Dawdy and O'Donnell investigated the feasibility and efficiency of a digital model for the automatic calculation of model parameters. For the practical purpose of estimating catchment runoff from precipitation, the use of hourly data limits the application of this model to those areas which have recording rainfall gauges.

Between the extremes of empirical formulae and anlytical solutions lies the fruitful area of scientific hydrology. Some of the special models and approaches listed earlier may be useful for deriving runoff from precipitation in the form required for an overall water-resource simulation program. But each must be analyzed for its utility in a specific case.

A more general approach is suggested in a recent study by Fiering. He observes that time-dependent relations between elements of streamflow and precipitation records are not consistent with simple rainfall-runoff functions. If such simple functions governed, the correlograms of both series would be strikingly similar; but in fact, for many sites they are remarkably different. The Fiering model demonstrates the plausibility of such differences and presents a technique for bringing the correlograms into harmony. While the model is not necessarily correct simply because it explains the differences between correlograms, it does point a way to a realistic transformation between precipitation records and streamflow events. The Fiering model uses the relevant statistical parameters of recorded precipitation sequences to derive a transformed set of dependencies among the streamflows which preserves the observed time-dependencies. This property is not guaranteed in any other rainfall-runoff model currently available. Although the Fiering model has been developed conceptually, further work is required to adapt it for use in a water-resource simulation program of the type discussed in this report.

Streamflow-Forecast Models

These models differ more in purpose than in concept from those discussed in the previous section. A precipitation-runoff model for an overall water-resource system simulation program provides an estimate of current runoff, for a given current and antecedent precipitation. A streamflow-forecast model, however, must provide estimates of future runoff, given information on the historic record of rainfall and runoff, current and antecedent rainfall and runoff, and available predictions of precipitation.

Models for forecasting river stage and discharge have the following components:

1. Quantitative precipitation forecasts issued by the Weather Bureau;
2. A graphical correlation technique for computing rainfall excess;
3. A unit graph computation subroutine to give distribution of runoff;
4. A streamflow routing subroutine; and
5. Where applicable, a reservoir routing subroutine.

The procedures now in use rely on an integrated index of moisture deficiency computed from antecedent precipitation and time of the year. In the standard forecast procedures now in use, rainfall intensity is not considered; only differences in store deviations are taken into account. Adjustment for exceptional conditions is achieved through subjective judgment. For improved accuracy, more complex methods of moisture accounting must be used.

The general conclusion of the research conducted by the Weather Bureau is that the multi-capacity basin accounting techniques is superior to that now used in predicting runoff from rainfall and other meteorological factors. However, a balance must be achieved between adequate representation of the physical process and timeliness of forecasts. The inclusion of a digital computer throughout river forecasting systems, as projected in the long-range plans of the Weather Bureau, will provide an opportunity to incorporate more complex hydrological techniques in the analysis. Although it has not been feasible in the past to collect detailed information on rainfall intensity on a synoptic basis, radar and improved communication and data handling facilities should permit the inclusion of intensity as one of the parameters in the analysis.

Streamflow-forecast models are available for some U.S. watersheds. Usually, these cover short periods—days, or 1 or 2 weeks at the most. Where snowmelt is a significant factor, periods of as long as a month or two are covered. Such forecasts are more reliable for downstream segments of large watersheds in humid regions than for small basins subject to extreme variations in precipitation (caused, for example, by summer thunderstorms).

Although much further research is required to develop streamflow-forecast models for use in water-resource system simulation models, approaches and techniques for making reasonably successful adaptations already exist. As large amounts of meteorological data from orbiting weather satellites become available, this capability will increase.

System Operation Models

If a water-resource simulation program is used to test the effects of weather modification, precipitation inputs must be substituted for runoff inputs. This in itself does not require modification of system operating subroutines. However, if the water-resource simulation program is to be used to test the effects of various levels of streamflow forecasting, subst ntial changes in operating policy subroutines are necessary.

In general, a key problem in constructing a water-resource system simulation program is the development of a good operating policy. Conceptually, the goal is to achieve an optimal operating policy, so that for any selected system design, maximum net values or benefits can be derived. In practice, this goal is not currently attainable, and a sub-optimal but flexible policy is the more realistic objective.

A system operating policy involves at least three kinds of storage, release and allocation decisions:

1. How to allocate storage or releases among purposes—e.g., for water supply, hydroelectric power, navigation, recreation, and flood control.
2. How to allocate storage or releases among storage reservoirs—e.g., among reservoirs in parallel and reservoirs in series.
3. How to allocate storage or releases among time periods. This may involve withholding releases in a current time period in order to make releases in subsequent time periods.

Allocation by Purpose.—In the absence of an optimal operating policy which can define the best combination of purposes, the general rule is to assign priorities to purposes, and attempt to meet the storage and release requirements of each purpose in terms of these priorities. The operating policy is made flexible so that, at input option, the priority sequences can be changed. No modifications of this general approach are necessary to handle weather modifications and forecasting problems.

Allocation by Reservoir.—There are two sub-problems: allocations for reservoirs in series, and allocations for reservoirs in parallel. For reservoirs in series, a sensible general guide is first to release from lower reservoirs, and then successively to release from the next-upstream reservoirs as required. This rule takes account of uncertainty of flows. It provides a "second chance" to capture unanticipated large inflows in excess of the storage capacity of upper reservoirs by storing them in lower reservoirs wherein space has first been provided. To the extent that flow forecasting reduces the uncertainty of inflows, this general guide is less applicable. Of course, many other factors supervene to modify this general guide: differential location of hydropower sites at reservoirs and intervening release requirements are examples.

For reservoirs in parallel, a general rule for allocating releases is known as the Space Rule. It is so named because it attempts to equate the ratio of the vacant storage space in each reservoir to total system storage space with the ratio of expected future inflows to each reservoir to total system inflows. In this way, the probabilities of spill in the next period, however defined, are equalized for each reservoir.

The Space Rule requires that some estimate of future inflows be made. In the absence of anything better, mean flows derived from the historic record can be used. Obviously, flow forecasting based upon current meteorological information can provide better estimates and hence better results. A statistical problem arises, however, because of correlation between the expected flows in the numerator and denominator of the ratio: the expectation of the ratio is not equal to the ratio of expectations. Fiering is currently working on a method of accounting for this correlation in the context of the Space Rule, and results are expected to be available in February 1968. The Space Rule is limited to allocating volume (or rate) of flow requirements, and suffers from a number of operational problems. However, when the adaptations being developed by Fiering are made, this general rule will provide a meaningful algorithm for allocating flow requirements from reservoirs.

Allocation by Time Period.—Under perfect certainty of flows and requirements, allocation by time period is a theoretically trivial but computationally formidable problem of assigning available flows in accordance with the optimal time pattern. Uncertainty, however, renders this allocation problem more difficult. Where there is a possibility of water shortage or floods, allocations by time period are necessary.

Economic losses are associated with water shortages; and this concept is introduced operationally in the simulation by means of an economic loss function, which may or may not be linear throughout or in segments of the function. For linear loss functions, the so-called normal operating policy is optimal: that is, requirements are met as they arise, and no water is held back to meet future requirements if it is needed in the current period.

For nonlinear loss functions, say quadratic, the normal operating policy is no longer optimal and some form of hedging is indicated. Young, of the Harvard Water Program, studied a wide variety of loss functions (including discontinuous, piecewise linear, and quadratic functions), using a dynamic programming model to derive optimal or near-optimal policies. He included in his models the capacity to forecast flows for the next period, attaching a given level of reliability to each forecast. His sensitivity analysis of the value of flow forecasting indicated that, for the particular set of loss functions analyzed, the gains in net benefits with increase in forecast reliability were modest. A few studies combining the Young algorithm with the Space Rule allocation procedure have shown that optimal policies are relatively more profitable in the operation of multiple-reservoir systems; but at this time this research is not sufficiently advanced to justify more specific inferences.

Problem of Extreme Flows.—The analysis of and operation for extreme flows offer prospects of incorporating weather forecasting and modifications into the framework of water-resource simulation programs. Existing simulation programs contain sub-programs for routing floods, predicting flood crests, operating irrigation, and power networks under conditions of water shortage, and the like. It appears possible to construct a subroutine package, to be added to a simulation program of the Lehigh-Delaware type. This subroutine would scan the state variables in each period, detect extreme conditions, and decide whether to implement weather modification. If modification were indicated, another subroutine would be entered, and appropriate calculations would be made to estimate the effect of the modification attempt on current and future hydrologic inputs to the system. Identical studies could then be run using the same design variables, with and without modification; and the economic performance could be determined for each alternative. With this approach, effective use would be made of the rainfall-runoff models discussed earlier in this paper.

Economic Effects of System Operation

The key concept (and technique) used to analyze short-term economic effects of system operation is the economic loss function. Typically, simulation of the operation of a water-resource system is carried on to meet specified resource product or service requirements, or "target outputs." Target outputs are evaluated by means of a long-run benefit-output function, with outputs assumed to be fully met at all times. When deficits are encountered in the course of simulation analysis, penalties are assigned to them in accordance with some estimated functional relationship between amount or degree of deficit and economic loss.

Conceptually the notion is straightforward; but implementing the concept can raise difficult problems of measurement. For such purposes as meeting hydroelectric power needs, measurement problems are manageable: electric utility systems have long employed the concepts of dump and replacement energy. Similarly, in irrigation practice, losses associated with water shortages have been measured. In flood control analysis, the flood damage-discharge function is a special form of the economic loss function, and there is extensive experience in constructing such flood damage-discharge functions. On the other hand, little or no work has been done in measuring economic losses from deficits in domestic and industrial water supply, from reductions in water quality, or from drawdowns below target reservoir levels established for recreation use.

Adopting a single-valued long-run benefit function and short-range economic loss function may be too simplistic an approach to measuring economic benefits and losses by computer simulation. Jacoby, of the Harvard Water Program, points out that in attempting to define the long-term benefit function some level or frequency of system failure is tacitly or explicitly denied. Yet, it is futile for a planner to guarantee a target output, however small, without admitting the possibility that the system may be unable to provide it. Consequently, some measure of unreliability should be associated with the long-term benefit function, but this unreliability need not be accounted for separately in a short-range loss function.

Jacoby also argues that even if a long-run benefit function can be uniquely defined, a small number of shortage experiences will move producers off the function. For example, a company which has suffered a major loss because of a water deficit may install emergency wells or some form of standby processing, so that if such a deficit recurs, it will be less damaging. This form of hazard insurance, with well-defined premiums, is not reflected in long-run benefit functions. Finally, Jacoby suggests that the use of least-cost alternative means of providing the output deficit to define the loss function is frequently inappropriate: it often happens that when the original resource is in short supply, the alternative is also in short supply; and the price of the alternative supply is therefore subject to sharp fluctuation.

His critique leads to the conclusion that short- and long-term benefit functions, valid at the start of a project, are subject to changes arising from human adjustment to adverse hydrologic experience. An expedient solution may be the development of a family of benefit and loss functions, with the choice of which member is to be applied being determined by asking the simulation program to examine the recent past for shortage occurrences.

A more general observation, derived from the work of White and Kates on human adjustment to floods, holds that short-run economic loss functions cannot meaningfully be developed without specific research on human reaction and adjustment to such crises as water shortages or floods. Reactions and adjustments are influenced by many factors: nature and type of organization or community involved, i.e., small business, large business, farmers, householders; intensity and persistence of shortage or flood; frequency of shortage or flood; and institutional means for counteracting or alleviating adverse effects.

If water-resource system simulation is to be used effectively to measure effects of weather modification and forecasting, economic loss functions which are conceptually valid and operationally useful are essential. The serious problems involved in devising operational functions present a challenge to model builders which research can help to meet.

Conclusions and Recommendations

It appears feasible to adapt water-resource system simulation programs of the Lehigh-Delaware type, developed by the Harvard Water Program, for use in testing the effectiveness of weather modification and streamflow forecasting measures. Such an adaptation could be accomplished by a moderate-sized research project, similar in scale and scope to the Harvard

Water Program's simulation work during the years 1962–1965. Such a project might suitably be undertaken by one of the water-resource research institutes or centers.

Before such adaptation is attempted, or at least concurrent with such an effort, research should be undertaken on major problems identified earlier in this report.

Generation of Synthetic Precipitation Records for Input to Simulation Models

Development of models for synthesis of precipitation is still in its early stage. There has been little application of synthetic precipitation sequences as inputs to water-resource simulation models. Work on synthetic precipitation models must be extended to make them suitable for use in water-resource system simulation.

Extension of Precipitation-Runoff Models

Both systems-oriented and component models of catchment behavior perform the function of producing runoff sequences from various precipitation patterns. Soil Conservation Service studies might be particularly enlightening in this regard.

For systems-oriented models, further research is needed to take adequate account of areal distribution of rainfall and of variable watershed response to different rainfall inputs.

For component models, further research is needed to generalize their use in arid and semi-arid hydrologic regimes and to extend their capability of using effectively these kinds of meteorological and hydrologic data routinely collected on most watersheds.

Also, further investigation is needed on the sensitivity of the system response to the component sub-systems variables, in order to simplify the models and to provide valuable guides in planning data collection programs.

Amplification and Testing of the Fiering Multi-Lag Correlogram Model, Using Precipitation Data as well as Runoff Data

This model uses the statistical characteristics of both runoff and precipitation events to account for discrepancies noted in flow correlograms. Resolution is obtained by including the effects on current flows of the flows of a number of earlier periods (instead of only the previous period, as in a simple Markov model). The goal here is to develop the equivalence of a generating model (based on the statistical parameters of both rainfall and runoff) to that of a model based on several antecedent flow events. Thus, when rainfall modification is assumed, by changing the actual or synthetic precipitation data, the statistical parameters of the rainfall can be changed accordingly, and the model will then yield the synthetic sequences of runoff which are appropriate for the modified precipitation.

Research on Testing the Applicability of Reservoir Release Allocation Rules (e.g., the Space Rule)

Perfect allocations can be achieved only with perfect foreknowledge, which is, of course, unattainable. As rainfall and runoff forecasting improves in reliability, allocation rules become more effective, if the rules are appropriate to the degree of reliability of the forecasts. Further research is required in these areas.

Research on the Utility of Hedging Rules for Complex Systems

Young has shown that for the single-reservoir, single-purpose case, hedging rules contribute little to improving net benefits for a wide range of economic loss functions. Hedging becomes more meaningful in operating a system when forecasting is more reliable. Further research is needed on the utility of hedging for multi-unit, multi-purpose systems, under various assumed degrees of forecasting reliability, along the lines of research currently being carried on by Fiering.

Research on Economic Loss Functions Under Various Assumed Conditions

Further study is also needed on economic loss functions associated with floods, droughts, deficits in target outputs for energy, recreation, and water supply. In particular, there is need to investigate the nature and shape of such functions under various assumed conditions: with no weather modification or forecasting; with weather modification; with forecasting. The behavioral relations and actions of farmers, industrial concerns, and householders also have to be investigated to determin how such groups react to various water management measures.

Research on Special Applications of Simulation Techniques

Special applications of simulation techniques to weather modification and weather forecasting problems, of different scope and scale than the Lehigh-Delaware type, would be desirable. An example would be development of *stochastic-physical* and *stochastic-economic* models to test the efficacy of cloud seeding (along the lines of the models developed at Harvard for investigating waterlogging and salinity in West Pakistan).

Although simulation techniques, when combined with rational-decision models, show promise in helping to assess the effectiveness of weather modification and forecasting, the problems of using and adapting these techniques and models to this purpose should not be underestimated. Much research is required before operational models will be available. But the potentional importance of weather modification and forecasting as instruments in resource management which can serve the economic and social needs of man points to the worthwhile nature of such research.

PART 4—A SIMULATION MODEL FOR THE STUDY OF SURFACE TEMPERATURE MODIFICATION

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Introduction

If one has an observed time series of temperature observations, say, $T = T_1, T_2, T_3, \ldots, T_n$, it is a simple matter to generate a modified series, T^*, such that

$$T^*_t = T_t + \epsilon_t,$$

where ϵ has a known distribution. If ϵ is sampled from a normally distributed population with mean u and standard deviation s, and if a sufficiently large sample is drawn, $\overline{T^*}$ will tend to equal $\overline{T} + u$. Such a modified time series, however, may not be at all useful in studying the economic impact of weather modification because it will not produce "observations" consistent with the physical properties of the atmosphere.

If a simulation model approach is to be useful in a study of the economic (social) impact of weather modification, it must meet certain requirements. Work done at the University of Missouri [1] during the past year has proceeded under the following restrictions:

1. The simulation model should be consistent with physical knowledge of the atmosphere.
2. The model should be consistent with known statistical properties of atmospheric events.
3. The model should be consistent with known relationships between atmospheric events and economic (social) events.

A model has been developed [2] which, it is believed, meets these three basic requirements. It is described here as a specific example of a simulation model that can be useful in studying the economic impact of weather modification. Further refinements are planned for this particular model; and other models (involving rainfall modification) are being prepared at the University of Missouri.

The Model in Schematic Form

The physical process chosen for the model is the deliberate creation of contrail cirrus clouds. The model is presented in schematic form in Fig. 1.

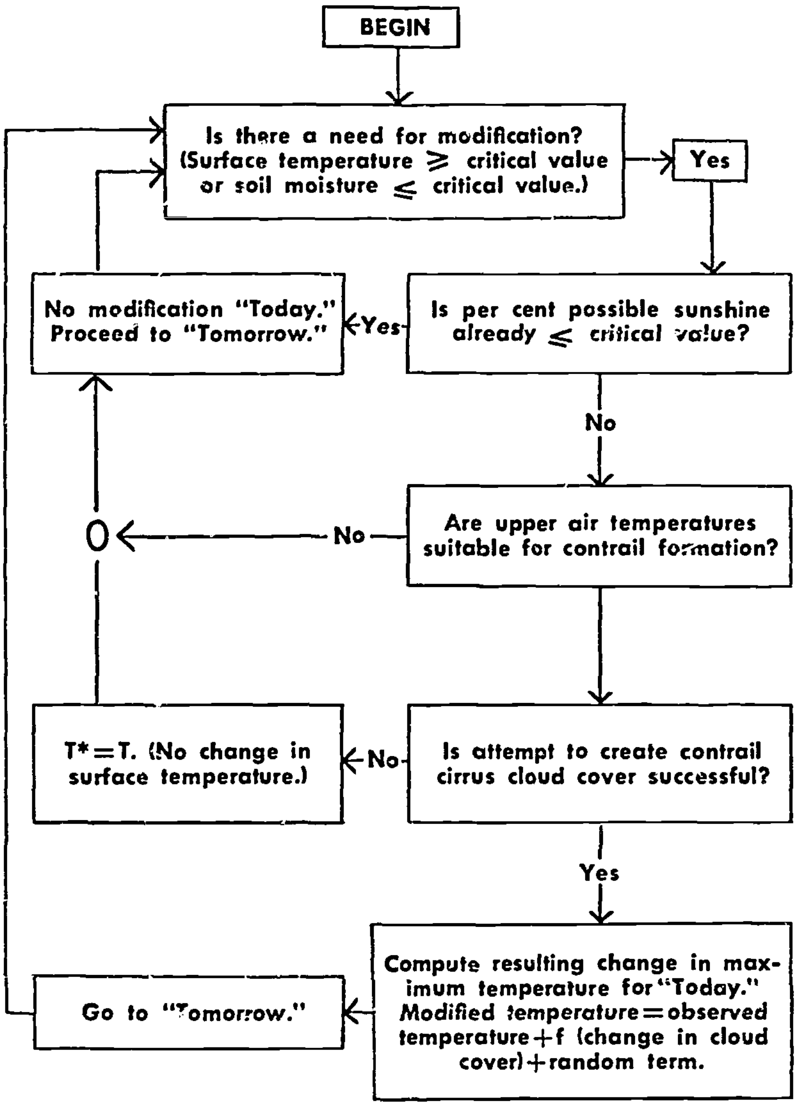

Fig. 1 Block Diagram of Conceptual Model

The Model in Detail

The initial question in the block diagram of Fig. 1, "Is there a need for modification?" is answered by first asking two other questions:

1. Is maximum temperature today expected to exceed a certain critical value?
2. Is available soil moisture [3] today estimated to be below a certain critical value?

If the answer to both questions is "no," the decision for "Today" is to make no attempt to modify.

These two questions seem appropriate for the economic (social) activities that are believed to be temperature-sensitive during the summer months in central Missouri. They may not be appropriate for other seasons of the year, or for other geographical locations. Choice of the critical values to use and of the elements to be considered will have an important influence on the final results of applying the model.

The kind of modification being simulated in the model is the creation of contrail cirrus clouds. If natural cloudiness is already abundant on the day in question, little effect can be gained from adding more cloudiness. Thus, it is pertinent to ask: "Is the percent possible sunshine less than some critical value?"

Given the need for modification and the lack of sufficient natural cloudiness, the next question is: "Are upper air temperatures suitable for contrail formation?" This question is answered by using an array of probability values developed by the U.S. Air Force Air Weather Service.[4] For a given pressure level in the atmosphere, the probability of contrail formation is

$$p \text{ (contrails)} = f(T),$$

where T is the ambient temperature.

To get some idea of the feasibility of contrail formation during the summer months over central Missouri, a frequency distribution of observed upper air temperatures was prepared, based on a 20-year sample from Columbia, Mo. The probability values obtained from the frequency distribution were then combined with the probability array developed by the Air Force study [5] to obtain the values shown in Table 1. These values indicated that suitable upper air temperatures do exist over central Missouri with sufficient frequency to allow use of the simulation model.

Table 1.—The Expected Probability of Contrail Formation Over Columbia, Mo.

Month	350 mb	300 mb	250 mb	200 mb	150 mb
June	*0.00	*0.00	0.06	0.45	0.86
July	*0.00	*0.00	0.03	0.31	0.93
August	*0.00	*0.00	0.03	0.55	0.91

*Probability <0.01.

The 20-year record of observed upper air temperatures for Columbia, Missouri, together with records of daily maximum and minimum surface temperatures,[6] precipitation and percent possible sunshine, provided the basic input data for applying the model. As an example, suppose the probability of contrail formation at the 200 millibar level "Today" was 0.70, and suppose further that the initial question concerning the need to modify could be answered in the affirmative. A uniformly distributed random number, U, would be generated such that $0.0 < U < 1.0$. If $U > 0.70$, it is assumed that an attempt to modify would be made, and that it would fail. If $U < 0.70$, success would be claimed. If the attempt to modify failed, the model would proceed to the next day, and the questions would begin anew. If success was claimed, then the effect on surface temperature would be computed.

A method for estimating the effect of increased amounts of cirrus was developed, based on observations of naturally occurring cirrus at Columbia, Missouri. Using the statistic "percent possible sunshine," a relationship was fitted [7] of the form

$$\Delta T = \hat{A} + \hat{B}(S) + \epsilon,$$

where ΔT equals the diurnal rise in temperature from the overnight low TN, to the afternoon high, TX. $\hat{A}$ and $\hat{B}$ are regression coefficients; S is the percent possible sunshine; and ϵ is a random, normally distributed number with mean zero and standard deviations.

If ΔT^* is the rise in temperature resulting from a day during which enough contrail cirrus was created to reduce percent sunshine from the observed value, S, to a lower value, $SMOD$, then

$$\Delta T^* = \hat{A} + \hat{B}\ (SMOD) + \epsilon, \text{ and}$$

$$TX^* = TN + \Delta T^*$$

The sample of data used to estimate $\hat{A}$, $\hat{B}$ and s produced regression coefficients that were different from zero at the 5 percent level of significance, and estimates of s that were rather large. It seems unlikely that a functional relationship can be found which will relate increases in cloudiness exactly to changes in surface air temperature.

Results of Applying the Model

The model was applied using different estimates of important parameters. The results are still being analyzed, but some preliminary conclusions are discussed here.

One interesting statistic concerns the estimated effect of modification on seasonal maximum temperatures. Table 2 shows modified extremes for three typical applications, as well as unmodified temperatures recorded at

Columbia, Mo. It should be noted that for some years, the modified seasonal extreme is the same as the unmodified.

Table 2.—Estimated Effect on Summer Maximum Temperatures on Days When Modification Is a Success

Year	No modification	Average decrease in Sunshine (percent)		
		.15	.25	.35
1946	104	102	103	110
1947	104	104	103	104
1948	98	98	98	96
1949	96	96	96	96
1950	95	95	95	94
1951	97	97	97	97
1952	105	105	105	105
1953	102	100	101	100
1954	113	104	106	103
1955	100	100	100	97
1956	101	99	99	99
1957	101	101	101	101
1958	97	95	94	95
1959	97	96	97	96
1960	100	99	99	99
1961	94	94	94	94
1962	103	99	97	97
1963	98	98	97	96
1964	103	100	101	100
1965	95	95	95	95

On days when no cirrus cloud modification is claimed, no resulting change in temperatures is expected. When the amount of cirrus clouds is increased in the model, however, temperatures decrease. Table 3 shows the estimated average decrease in temperatures for each summer when modification is a success.

Analysis of Variance

Meteorological data from a 20-year period were used in each application of the model. Six different variables were computed on each run and used to summarize the results, which were then subjected to analysis of variance. The variables considered were: (1) difference in amount of irrigation water required for modified and unmodified models; (2) difference in mean temperatures for modified and unmodified models; (3) average of difference between modified and unmodified maximum temperatures over days when modification occurred; (4) average of difference between modi-

Table 3.—*Average Decrease in Maximum Temperatures on Days When Modification is a Success*

Year	Average decrease in sunshine (percent)		
	.15	.25	.35
1946	2.5	3.2	4.1
1947	3.3	4.0	4.6
1948	3.3	4.1	4.0
1949	1.3	1.9	3.2
1950	1.7	2.4	3.0
1951	2.5	3.0	2.6
1952	4.5	5.3	6.2
1953	4.3	5.2	5.6
1954	4.8	5.8	6.9
1955	3.0	3.9	4.5
1956	4.1	5.0	6.5
1957	4.1	5.0	5.7
1958	2.7	3.2	4.7
1959	3.0	5.5	6.1
1960	2.0	5.5	5.5
1961	4.0	3.1	2.6
1962	3.5	4.7	5.6
1963	3.3	5.7	4.7
1964	3.0	4.7	5.0
1965	2.0	1.8	2.6

fied and unmodified maximum temperatures over days when modification was needed; (5) difference between modified and unmodified extreme temperatures during summer months; and (6) difference between modified and unmodified models in amount of soil moisture left at the end of the growing season.

One factor left to the choice of investigators was the average decrease in percent sunshine on days when modification was to occur. In our applications, values of 0.15, 0.25, and 0.35 were used. Another factor left to choice was the threshold value of maximum temperature to be used in defining the need for modification. In our case, values of 85 and 90°F were selected. Other combinations are surely possible if sufficient computer time is available.

Details of the results of the analysis are too numerous to present here. In brief, however, the results indicated that the model was producing a modified temperature series with components of variance that could reasonably be attributed to changes in the amount of cloudiness claimed. The model, in its present form, however, does not produce significant components of variance in soil moisture.

Conclusions

The simulation model described can produce a useful modified series of temperature values. These in turn can be used as reasonable estimates of what one would expect if summer cirrus clouds over Missouri were modified by creation of a sufficient number of contrails. The model requires further physical verification under carefully designed experimental procedures.

Work is now in progress to apply this model to simulation experiments involving the effect of temperature modification on electric power demand, dairy production, crop production and other weather-sensitive operations.

FOOTNOTES

1. Supported by National Science Foundation Grant No. GA 557.
2. More complete details about this model are contained in Murray L. Nicodemus, "A Simulation Technique for Modification of Surface Temperature," M.S. thesis, University of Missouri, August 1967.
3. Computed by a method developed by Thornthwaite. See C. W. Thornthwaite and J. R. Mather, *The Water Balance*, Publications in Climatology, vol. VIII, No. 1, Drexel Institute of Technology, Laboratory of Climatology, Centerton, N.J., 1955.
4. U.S. Air Force, *Forecasting Condensation Trails*, Air Weather Service Manual, 1960, pp. 105–110.
5. *Ibid.*
6. Surface temperature is the temperature observed in a Standard Weather Bureau Instrument Shelter.
7. The following estimates were obtained from sample data: $\hat{A}=13.3$, $\hat{B}=.12$, $s=3.95$.

Appendix XI

REMARKS ON CLIMATE ENVIRONMENTAL DESIGNS

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Now that man is capable of passing beyond the domain of the earth altogether, "The Human Dimensions of the Atmosphere" would seem to have become an all-inclusive term for all measures and magnitudes contained within the gaseous envelope of our planet. But I assume that the adjective is intended to refer to the dimensions of man's earthbound existence. Personally I am most interested in the role that climate does, or should play in the life and design of our cities.

Man's total response to any set of weather conditions usually has many apparently independent and very often contradictory aspects. The temptations of the warm Florida climate are made even more irresistible by air-conditioning of homes and hotels. Since the emphasis upon the component parts differ from one case to another, it may help to have a list of the more obvious tactical elements of man's strategy in attempting to deal with the problems of climate.

We may simply take advantage of beneficial features of climate in a more or less passive manner; literally or figuratively basking in the sun or the snow, as it were. Modern advertising combined with increased leisure and longevity have tremendously boosted the importance of this primitive *modus operandi*. Secondly, we may make adjustments in our ways of living to make unfavorable conditions easier to bear, for example, adopting the siesta habit when temperatures rise too high. Thirdly, we may take protective measures against the climate by housing, clothing, and in many other ways. Adjustment and protection are not necessarily the same, either in method or results. Many of the adjustments people from cold climates are wont to make in the tropics may help them achieve a more comfortable life from day to day, but not a longer one. Fourthly, we may attempt to modify the physical characteristics of the weather itself, and, fifthly, we may seek psychosomatic compensations for unpleasant attributes, and reinforcements for enjoyable features of the climate in the design of our man-made environment. My thoughts, for whatever they may be worth, are mostly concerned with the possibilities of the fourth, and, particularly of the fifth line of attack.

Efforts to exploit or abate the physical effects of sun, wind, heat or cold, moisture, and other aspects of climate by the design and orientation of buildings and the layout of towns and villages go far back into antiquity. A good review of the subject was published by Aronin [1] more than a dozen years ago. But, in spite of the long history of our endeavors in the field, it does not seem unfair to say that our advances lag far behind our technical progress in other areas of enterprise. Perhaps indoor air-conditioning and our enclosure in automotive containers during so much of the time nominally spent outdoors have made us indifferent to the possibilities of climatic modifications by environmental design. Even the knowledge that has been gained has found disappointingly little application.

It is well known that the climate of cities differs from that of the surrounding countryside. But the proven ability of urban forms and functions to modify atmospheric conditions has rarely been used in any significant or systematic manner to improve upon the circumstances of life in our cities. Instead we simply accept the blessings of miseries of our urban climates as fortuitous byproducts of other designs or developments. Some of the possibilities are crudely obvious such as the projection of a street plan that will lessen instead of augmenting the strength and discomforts of prevailing winter winds. We still have cities where many of the streets seem arranged to act as reinforcing tunnels or, at least, as easy access lanes for almost every blizzard of the wintry season. But most of the possibilities will rest on far more subtle relationships between city and atmosphere, that will require intensive study before their potential benefits can be realized. One of my recommendations is therefore the creation of an adequate program of research on the relationships between urban patterns of forms and functions and atmospheric activity, with the definite purpose of seeking ways to influence the relationships to urban advantage. But the comforts we may achieve by psychosomatic means may, in the end, prove even more important for the pleasures of urbanism than anything we can do about the weather itself, other than defense against its assaults upon our persons and our homes.

It is amusing to speculate upon the possible relationships between climate and the patterns of thoughts, feelings, and behavior we encounter in various parts of the world. Is it pure coincidence that, at least within western civilization, the gaudiness, scale, and intensity of seasonal fiestas seem inversely proportional to the differences of the natural seasons. Does carnival in Nice and springtime in Norway fulfill the same human need for a periodic sense of renewal or catharsis, by the grace of nature or by the design of man when nature is ungracious? Could the development of visually dramatic styles of personal behavior possibly be favored by a lack of visually dramatic changes in the environment? Even such questions as these may some day become important in trying to determine how far we should push the cumulative standardization of all the elements comprising our non-human surroundings. In the meantime it may be well to remember that in all of man's history ours is the first century in which "roughing it" has come to mean a pleasing and popular form of diversion, and not disagreeable state of discomfort. But there are also simpler and more immediate problems of modern existence calling for joint efforts from the students of the atmosphere and the designers of our habitat.

It is an old and trite saying that what you don't know can't hurt you. The statement contains a large grain of truth in regard to our reactions to the conditions of the air, within wide limits of tolerance. It is particularly true with reference to temperature. We can bear a great deal of cold weather with equanimity and little ill effect so long as we do not feel cold, or we can suffer excessively from a rather slight exposure if our sense of misery is reinforced by features of the milieu that have nothing to do with temperature except in their psychological effects. We all speak of persons, buildings or entire scenes looking cold or warm, and are attracted or repelled according to whether we ourselves feel chilly or hot at the moment. There is more to this than empty words. Many years ago when the early, still experimental fluorescent tubes, with their "cold" bluish white light were introduced during the cold season in some of the halls of a museum under my responsibility, the guards immediately began to report complaints from the public about the chilly temperatures of these halls in comparison with the others, although the thermometers registered the same temperature everywhere. The existence of such psychosomatic relationships is too well known to require any elaboration here. The point to be made is that the beneficial possibilities offered by these effects for the design of enjoyable surroundings, have generally been neglected and are often even contravened in the creation of our man-made entourage. A few architects have made valiant, and sometimes brilliant, but isolated, attempts to make the mood of our shelter fit the prevailing disposition of the climate it is in. But most of our modern architecture seems primarily aimed at looking handsome in a sunny rendering or, better still, in a sunny photography on the pages of the Architectural Record, regardless of whether there are 60 or 360 days of sunshine, or whether the summer lasts two months or all year round, where the building stands. But perhaps the architects are not too much to blame for the way things are. They have had little or no help or encouragement from the students of weather, or of psychology for that matter.

Weather modification should be thought of as an overall strategy combining two tactical operations; direct improvement of actual atmospheric living conditions, and psychosomatic compensations for unfavorable, or reinforcements of feebly favorable aspects of climate that are not amenable to change by reasonable effort. In urban precincts the possibilities of psychosomatic amelioration are probably much greater than the potential benefits of trying to amend the weather itself but to succeed in the tactical mission of the psychosomatic approach we must first secure the close cooperation of climatologists, psychologists, sociologists and environmental designers. It is my second recommendation that an adequate team be organized to make a pilot study of some existing situations, a survey of psychological responses to atmospheric conditions and to environmental forms, and a search for methods of investigation that might yield further insights into our needs and the means of their fulfillment.

It would seem desirable to select for such a first examination two or more separate regions sharing wide differences of climate, architectural styles, and urban forms. The following areas may suggest themselves as good prototype locations to choose from: the north-eastern urban belt from Philadelphia to Boston. The South Florida conurbation centered around Miami. The shores of Lake Michigan from Gary to Milwaukee, including Chicago. And the San Francisco Bay region. From the meteorologists one would want an intensive and detailed analysis of climate and micro-climates within each of the selected territories. The data should be gathered and classified with due consideration of the findings of the psychologists in regard to scales of significance for our sense of comfort or discomfort. A fine distinction in one part of the spectrum may be as important as a large difference in another portion. From psychologists and sociologists we would get further evaluations of the impact of climate and weather upon the human condition. Simple statistics, even with variably adjusted precision of recording, will not suffice as a basis for rational planning. It will be a long time before we can create cityscapes that we will be able to change as we change our underwear with the seasons, and, until we learn to do so, we need to know whether it is more important to mitigate two weeks of blistering cold or two days of broiling heat, or *vice versa*, to mention only a simple and crudely obvious illustration. Psychologists and sociologists, working in conjunction with architects and urban planners would examine the relationship between environmental design features and human responses to weather and climate. From such investigations, and from subsequent research stimulated by the pilot project, it should ultimately become possible to establish goals of environmental design for any location in any climate, for proper integration with the answers to other demands upon the milieu. Such clarification of purposes and methods would in no way restrict the creative scope of our environmental designers, any more than a knowledge of pigments and an understanding of composition limit the painter at his easel.

FOOTNOTE

1. Jeffrey Ellis Aronin: Climate & Architecture, Reinhold Publishing Co., New York, 1953.

Appendix XII

BIBLIOGRAPHY ON HUMAN DIMENSIONS OF THE ATMOSPHERE

W. R. DERRICK SEWELL and MICHAEL J. BROWN, *University of Victoria, Victoria, British Columbia*

Introduction

During the past few years, interest in the human use and modification of the atmosphere has increased. This interest has stemmed in part from the problems posed by mounting losses from pollution and extreme weather events, and in part from man's increasing ability to manipulate particular atmospheric variables. Until now, however, it has been difficult to gauge both the magnitude of the interest in such problems, and the extent of contributions to solve them. Although comprehensive bibliographies have been prepared on the physical dimensions of the atmosphere and its modification,[1] no up-to-date, extensive bibliography has been prepared on the human dimensions of the atmosphere. The present report is an attempt to overcome this deficiency. While its coverage is broad, it does not contain a complete list of references. This would have required much more time than the present compilers had available, and in any event some kind of selection seemed desirable. A number of the entries included contain useful bibliographies on the topics discussed in them.[2]

For present purposes it was decided to include items on the following topics:

1. General works covering matters of broad interest relating to human uses of the atmosphere.
2. Physical aspects of the atmosphere, its uses, and its modification.
3. Economic evaluation of alternative adjustments to weather and climate, particularly the techniques of identification and measurement required for this purpose.
4. Economic impacts of weather or weather modification on particular activities.
5. Impacts of weather or weather modification on particular regions.
6. Institutional aspects of the management of atmospheric resources, including law, administrative arrangements, and public policies.
7. Human behavior, including discussions of reactions to variations

in weather and climate in different areas, effects on physiology, psychology, etc., and the role of perceptions of and attitudes to weather modification.

8. Information and research, including discussions of the use of weather information, and evaluations of research on weather, on the use of weather information, and on weather modification.

Coverage

The entries in this bibliography are drawn mainly from literature that has appeared since 1957. This date was selected because the first major bibliography on economic and social aspects of weather modification appeared in that year.[3] Most of the literature on this subject in any case has been published since that date. This bibliography expands considerably on the coverage of two other bibliographies that appeared in the intervening period.[4]

The problem of selecting items for any bibliography is always a difficult one, and so also is the matter of classification. In the present bibliography, a number of items are included which do not relate directly to the weather or human adjustment to it; but they do have relevance to problems that need to be solved. For example, in the section on economic evaluation, some entries deal with techniques of measurement developed for the evaluation and development of water resources or agriculture; and these techniques may have useful applications to weather problems.

Trends

The present bibliography reveals a number of important trends in the literature. Contributions relating to physical aspects of the use and modification of the atmosphere continue to mount (only selected items are included here). Contributions relating to economic aspects are now increasing fairly rapidly, but only minor interest is indicated in sociological and psychological aspects. The literature on legal problems is increasing, but interest in political and administrative problems still lags behind.

These trends, of course, reflect the perceived importance of problems of managing atmospheric resources. Until recently the atmosphere was regarded as a free good, available to anyone to use in whatever way he wished, where and when he wanted to do so; and the main problems perceived related to determining the composition and dynamics of the atmosphere. However, man's increasing ability to manipulate the atmosphere, the growing losses resulting from severe weather events, and the impacts of atmospheric pollution have now aroused the interest of social scientists, especially those concerned with public policy aspects of resource management. To some extent, social scientists have been able to bring to bear concepts and techniques developed in studies of other resources, particularly water resources. A number of other contributions have provided valuable insights into the management of atmospheric resources and have also added to developments in theory in the disciplines involved. As more funds are made available for social science research relating to the atmosphere, and as more training programs in this field are initiated, the present imbalance between literature on physical aspects of uses of the atmosphere and contributions on the human dimensions of these uses should be redressed.

FOOTNOTES

1. See especially American Meteorological Society, *Meteorological and Geophysical Abstracts: Bibliographies on Weather Modification*, vol. 6, No. 10, October 1955; vol. 11, No. 12, December 1960; and vol. 15, No. 7, July 1964. See also Donald L. Gilman et al., *Weather and Climate Modification*, U.S. Government Printing Office, Washington, D.C., 1961.
2. See, for example, the following chapters in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification*, University of Chicago, Department of Geography Research Paper No. 105, Chicago, Ill., 1966; Marston Bates, "The Role of Weather in Human Behaviour," pp. 393–407; Edward A. Ackerman, "Economic Analysis of Weather," pp. 61–76; and Evon Z. Vogt, "Some Implications of Weather Modification for Tribal Societies," pp. 373–392. See also William L. Thomas, ed., *Man's Role in Changing the Face of the Earth*, University of Chicago Press, Chicago, Ill., 1956; Howard J. Critchfield, *General Climatology*, Prentice-Hall, Englewood Cliffs, N.J., 1960; and Jack C. Oppenheimer, "The Legal Situation," in U.S. Advisory Committee on Weather Control, *Final Report*, U.S. Government Printing Office, Washington, D.C., 1957, vol. II, pp. 209–232. Bibliographies also accompany the various appendices to the Final Report of the Task Group on the Human Dimensions of the Atmosphere.
3. See U.S. Advisory Committee on Weather Control, "Bibliography on Weather Modification and Cloud Physics," in *Final Report*, U.S. Government Printing Office, Washington, D.C., 1957, vol. II, pp. 322–396.
4. See W. R. D. Sewell, ed., op. cit., pp. 409–420; and Donald Gilman et al., op. cit.

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