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WEATHER MODIFICATION:
PROGRAMS, PROBLEMS, POLICY, AND
POTENTIAL

PREPARED AT THE REQUEST OF
HON. HOWARD W. CANNON, *Chairman*
COMMITTEE ON COMMERCE,
SCIENCE, AND TRANSPORTATION
UNITED STATES SENATE



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(II)

LETTER OF TRANSMITTAL

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
November 15, 1978.

To the members of the Committee on Commerce, Science, and Transportation, U.S. Senate:

I am pleased to transmit herewith for your information and use the following report on "Weather Modification: Programs, Problems, Policy, and Potential."

The report was prepared at my request by the Congressional Research Service under the direction of Dr. Robert Morrison, Specialist in Earth Sciences, Science Policy Research Division. We thank Dr. Morrison and the others involved in the study for their extremely thorough and scholarly report. Substantial material on almost all areas of weather modification are included and the report will provide the committee with an excellent reference source for future deliberations on the subject.

The completion of the report is particularly timely due to the upcoming recommendations expected from the Weather Modification Advisory Board and the Department of Commerce (as directed by Public Law 94-490) on the future Federal role in weather modification.

JAMES B. PEARSON,
Ranking minority member.

LETTER REQUESTING STUDY

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
WASHINGTON, D.C., *July 30, 1976.*

Dr. NORMAN A. BECKMAN,
*Acting Director, Congressional Research Service,
Library of Congress, Washington, D.C.*

DEAR DR. BECKMAN: Weather modification, although a relatively young science, has over the years stimulated great interest within the scientific, commercial, governmental, and agricultural communities. Such responses are readily understandable. Weather-related disasters and hazards affect virtually all Americans and annually cause untold human suffering and loss of life and result in billions of dollars of economic loss to crops and other property. While weather modification projects have been operational for nearly 25 years and have been shown to have significant potential for preventing, diverting, moderating, or ameliorating the adverse effects of such weather related disasters and hazards, I am greatly concerned regarding the lack of a coordinated Federal weather modification policy and a coordinated and comprehensive program for weather modification research and development. This fact is all the more disturbing in view of the manifest needs, and benefits, social and economic, that can be associated with weather modification activities. These deficiencies in our Federal organizational structure have resulted in a less than optimal return on our investments in weather modification activities and a failure, with few exceptions, to recognize that much additional research and development needs to be carried out before weather modification becomes a truly operational tool.

Reports and studies conducted by such diverse organizations as the National Academy of Sciences, the National Advisory Committee on Oceans and Atmosphere, the General Accounting Office, and the Domestic Council have highlighted the lack of a comprehensive Federal weather modification policy and research and development program. Hearings that I chaired in February of this year reinforced my concerns regarding the wisdom of our continued failure to implement a national policy on this very important issue.

I am therefore requesting the Congressional Research Service to prepare a comprehensive report on weather modification. This report should include a review of the history and existing status of weather modification knowledge and technology; the legislative history of existing and proposed domestic legislation concerning weather modification; socio-economic and legal problems presented by weather modification activities; a review and analysis of the existing local, State, Federal, and international weather modification organizational

structure; international implications of weather modification activities; and a review and discussion of alternative U.S. and international weather modification policies and research and development programs.

If you have any questions with respect to this request, please contact Mr. Gerry J. Kovach, Minority Staff Counsel of the Senate Commerce Committee. He has discussed this study with Mr. Robert E. Morrison and Mr. John Justus of the Science Policy Division, Congressional Research Service.

Very truly yours,

JAMES B. PEARSON,
U.S. Senator.

LETTER OF SUBMITTAL

THE LIBRARY OF CONGRESS,
CONGRESSIONAL RESEARCH SERVICE,
Washington, D.C., June 19, 1978.

HON. JAMES B. PEARSON,
Committee on Commerce, Science, and Transportation,
U.S. Senate, Washington, D.C.

DEAR SENATOR PEARSON: The enclosed report, entitled "Weather Modification: Programs, Problems, Policy, and Potential," has been prepared by the Congressional Research Service in response to your request.

The study reviews the history, technology, activities, and a number of special aspects of the field of weather modification. Activities discussed are those of the Federal, State, and local governments, of private organizations, and of foreign nations. Consideration is given to international, legal, economic, and ecological aspects. There are also an introductory chapter which includes a summary of issues, a chapter discussing inadvertent weather and climate modification, and a chapter summarizing recommendations from major Federal policy studies.

The study has been coordinated by Dr. Robert E. Morrison, Specialist in Earth Sciences, Science Policy Research Division, who also prepared chapters 1, 2, 3, 5, 7, 8, and 9 as well as the Summary and Conclusions. Mr. John R. Justus, Analyst in Earth Sciences, and Dr. James E. Mielke, Analyst in Marine and Earth Sciences, both of the Science Policy Research Division, contributed chapters 4 and 6, respectively. Chapter 10 was prepared by Mrs. Lois B. McHugh, Foreign Affairs Analyst, Foreign Affairs and National Defense Division. Chapter 11 was written jointly by Mrs. Nancy Lee Jones, Legislative Attorney, and Mr. Daniel Hill Zafren, Specialist in American Public Law, both of the American Law Division. Dr. Warren Viessman, Jr., Senior Specialist in Engineering and Public Works, contributed chapter 12; and Mr. William C. Jolly, Analyst in Environmental Policy, Environment and Natural Resources Division, was responsible for chapter 13. In addition, appendixes C, F, Q, and R were assembled by Mrs. McHugh; appendixes D and S were prepared by Mrs. Jones; and information in the remaining appendixes was collected by Dr. Morrison.

I trust that this report will serve the needs of the Committee on Commerce, Science, and Transportation as well as those of other committees and individual Members of Congress who are concerned with weather modification. On behalf of the Congressional Research Service, I wish to express my appreciation for the opportunity to undertake this timely and worthwhile assignment.

Sincerely,

GILBERT GUDE,
Director.

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SUMMARY AND CONCLUSIONS

Weather modification is generally considered to be the deliberate effort to improve atmospheric conditions for beneficial human purposes—to augment water supplies through enhanced precipitation or to reduce economic losses, property damages, and deaths through mitigation of adverse effects of hail, lightning, fog, and severe storms. Not all weather modification activities, however, have been or can be designed to benefit everyone, and some intentional operations have been used, or are perceived to have been used, as a weapon of war to impede the mobility or tactical readiness of an enemy. Furthermore, environmental change is also effected unintentionally and without any purpose at all, as man inadvertently modifies the weather and climate, whether for better or worse scientists are not certain, through activities such as clearing large tracts of land, building urban areas, and combustion of fossil fuels.

Historically, there have been attempts, often nonscientific or pseudo-scientific at best, to change the weather for man's benefit. Until the 20th century, however, the scientific basis for such activities was meager, with most of our current understanding of cloud physics and precipitation processes beginning to unfold during the 1930's. The modern period in weather modification is about three decades old, dating from events in 1946, when Schaefer and Langmuir of the General Electric Co. demonstrated that a cloud of supercooled water droplets could be transformed into ice crystals when seeded with dry ice. Soon afterward it was discovered that fine particles of pure silver iodide, with crystal structure similar to that of ice, were effective artificial ice nuclei, and that seeding clouds with such particles could produce ice crystals at temperatures just below freezing. Silver iodide remains the most often used material in modern "cloud seeding."

By the 1950's, many experimental and operational weather modification projects were underway; however, these early attempts to augment precipitation or to alter severe storm effects were often inconclusive or ineffective, owing to improper experimental design, lack of evaluation schemes, and the primitive state of the technology. Through research programs over the past two decades, including laboratory studies and field experiments, understanding of atmospheric processes essential to improved weather modification technology has been advanced. Sophisticated evaluation schemes have been developed, using elaborate statistical tools; there has also been improvement in measuring instruments and weather radar systems; and simulation of weather processes using numerical models and high speed computers has provided further insights. Meanwhile, commercial weather modifiers, whose number decreased dramatically along with the total area of the United States covered by their operations after the initial surge of the 1950 era, have grown in respectability and competence, and their operations have incorporated improvements as they benefited from their accumulated experience and from the re-

sults of research projects. Since such operations are designed for practical results, such as increased precipitation or reduced hail, however, the sophisticated evaluation procedures now used in most research projects are most often not used, so that the effectiveness of the operations is frequently difficult to assess.

Weather modification is at best an emerging technology. Progress in development of the technology over the past 30 years has been slow, although there has been an increased awareness of the complex nature of atmospheric processes and a steady improvement in basic understanding of those processes which underlie attempts at deliberate modification of weather phenomena. Though most cloud-seeding practices are based on a common theory and form the basis for a number of seeding objectives, there are really a series of weather modification technologies, each tailored to altering a particular atmospheric phenomenon and each having reached a different state of development and operational usefulness. For example, cold fog clearing is now considered to be operational, while, at the other extreme, the abatement of severe storms such as hurricanes remains in the initial research phase. Development progress for each of these technologies appears to be much less a function of research effort expended than a dependence on the fundamental atmospheric processes and the ease by which they can be altered. There continues to be obvious need for further research and development to refine those few techniques for which there has been some success and to advance technology where progress has been slow or at a virtual standstill.

The following summary provides a reasonably accurate assessment of the current status of weather modification technology:

1. The only routine operational projects are for clearing cold fog. Research on warm fog has yielded some useful knowledge and good models, but the resulting technologies are so costly that they are usable mainly for military purposes and very busy airports.

2. Several longrunning efforts to increase winter snowpack by seeding clouds in the mountains suggest that precipitation can be increased by some 15 percent over what would have happened "naturally."

3. A decade and a half of experience with seeding winter clouds on the U.S. west coast and in Israel, and summer clouds in Florida, also suggest a 10- to 15-percent increase over "natural" rainfall. Hypotheses and techniques from the work in one area are not directly transferable to other areas, but will be helpful in designing comparable experiments with broadly similar cloud systems.

4. Numerous efforts to increase rain by seeding summer clouds in the central and western parts of the United States have left many questions unanswered. A major experiment to try to answer them—for the High Plains area—is now in its early stages.

5. It is scientifically possible to open holes in wintertime cloud layers by seeding them. Increasing sunshine and decreasing energy consumption may be especially relevant in the northeastern quadrant of the United States.

6. Some \$10 million is spent by private and local public sponsors for cloud-seeding efforts, but these projects are not designed as scientific experiments and it is difficult to say for sure that operational cloud seeding causes the claimed results.

7. Knowledge about hurricanes is improving with good models of their behavior. But the experience in modifying that behavior is primitive so far. It is inherently difficult to find enough test cases, especially since experimentation on typhoons in the Western Pacific has been blocked for the time being by international political objections.

8. Although the Soviets and some U.S. private operators claim some success in suppressing hail by seeding clouds, our understanding of the physical processes that create hail is still weak. The one major U.S. field experiment increased our understanding of severe storms, but otherwise proved mostly the dimensions of what we do not yet know.

9. There have been many efforts to suppress lightning by seeding thunderstorms. Our knowledge of the processes involved is fair, but the technology is still far from demonstrated, and the U.S. Forest Service has recently abandoned further lightning experiments.¹

Modification processes may also be initiated or triggered inadvertently rather than purposefully, and the possibility exists that society may be changing the climate through its own actions by pushing on certain leverage points. Inadvertently, man is already causing measurable variations on the local scale. Artificial climatic effects have been observed and documented on local and regional scales, particularly in and downwind of heavily populated industrial areas where waste heat, particulate pollution and altered ground surface characteristics are primarily responsible for the perceived climate modification. The climate in and near large cities, for example, is warmer, the daily range of temperature is less, and annual precipitation is greater than if the cities had never been built. Although not verifiable at present, the time may not be far off when human activities will result in measurable large-scale changes in weather and climate of more than passing significance. It is important to appreciate the fact that the role of man at this global level is still controversial, and existing models of the general circulation are not yet capable of testing the effects in a conclusive manner.

Nevertheless, a growing fraction of current evidence does point to the possibility of unprecedented impact on the global climate by human activities, albeit the effects may be occurring below the threshold where they could be statistically detected relative to the record of natural fluctuations and, therefore, could be almost imperceptible amid the ubiquitous variability of climate. But while the degree of influence on world climate may as yet be too small to detect against the background of natural variations and although mathematical models of climatic change are still imperfect, significant global effects in the future are inferred if the rates of growth of industry and population persist.

For over 30 years both legislative and executive branches of the Federal Government have been involved in a number of aspects of weather modification. Since 1947 about 110 weather modification bills pertaining to research support, operations, grants, policy studies, regulations, liabilities, activity reporting, establishment of panels and committees, and international concerns have been introduced in the Con-

¹ Weather Modification Advisory Board. "A U.S. Policy to Enhance the Atmospheric Environment," Oct. 21, 1977. In testimony by Harlan Cleveland. Weather modification. Hearing before the Subcommittee on the Environment and the Atmosphere, Committee on Science and Technology, U.S. House of Representatives, 95th Cong., 1st sess., Oct. 26, 1977, Washington, U.S. Government Printing Office, 1977. pp. 28-30.

gress. Resolutions, mostly concerned with using weather modification as a weapon and promotion of a United Nations treaty banning such activities, have also been introduced in both houses of the Congress; one such resolution was passed by the Senate.

Six public laws specifically dealing with weather modification have been enacted since 1953, and others have included provisions which are in some way relevant to weather modification. Federal weather modification legislation has dealt primarily with three aspects—research program authorization and direction, collection and reporting of information on weather modification activities, and the commissioning of major policy studies. In addition to direction through authorizing legislation, the Congress initiated one major Federal research program through a write-in to an appropriations bill; this program regularly receives support through additional appropriations beyond recommended OMB funding levels.

There are two Federal laws currently in effect which are specifically concerned with weather modification. Public Law 92-205, of December 18, 1971, and its amendments requires the reporting of all non-Federal activities to the Secretary of Commerce and publication "from time to time" of summaries of such activities by the Secretary of Commerce.² The National Weather Modification Policy Act of 1976 (Public Law 94-490), enacted October 13, 1976, directed the Secretary of Commerce to conduct a major study on weather modification and to submit a report containing a recommended Federal policy and Federal research program on weather modification. The Secretary appointed a non-Government Weather Modification Advisory Board to conduct the mandated study, the report on which is to be submitted to the Secretary for her review and comment and subsequent transmittal to the President and the Congress during 1978. It is expected that, following receipt of the aforementioned report, the Congress will consider legislation on Federal weather modification policy, presumably during the 96th Congress.

Congressional interest in weather modification has also been manifested in a number of hearings on various bills, in oversight hearings on pertinent ongoing Federal agency programs, in consideration of some 22 resolutions having to do with weather modification, and in commissioning studies on the subject by congressional support agencies.

The principal involvement in weather modification of the Federal Government has been through the research and development programs of the several Federal departments and agencies. Although Federal research programs can be traced from at least the period of World War II, the programs of most agencies other than the Defense Department were not begun until the 1950's and 1960's. These research and development programs have been sponsored at various times by at least eight departments and independent agencies—including the Departments of Agriculture, Commerce, Defense, Energy, Interior, and Transportation, the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF). In fiscal year

² Although Federal agencies were excluded from the requirements of this act, upon mutual agreement, the agencies also submit information on their weather modification projects to the Secretary of Commerce, so that there is a single repository for information on all weather modification activities conducted within the United States.

1978 six agency programs were reported, those of Transportation and NASA having been phased out, while that of Agriculture was severely curtailed.

Total funding for Federal weather modification research in fiscal year 1978 is estimated at about \$17 million, a decline from the highest funding level of \$20 million reached in fiscal year 1976. The largest programs are those of the Departments of Interior and Commerce and of the NSF. The NSF has supported weather modification research over a broad spectrum for two decades, although its fiscal year 1978 funding was reduced by more than 50 percent, and it is not clear that more than the very basic atmospheric science supportive of weather modification will be sponsored hereafter by the Foundation.

The present structure of Federal organization for weather modification research activities is characterized essentially by the mission-oriented approach, whereby each of the agencies conducts its own program in accordance with broad agency goals or under specific directions from the Congress or the Executive. Programs have been loosely coordinated through various independent arrangements and/or advisory panels and particularly through the Interdepartmental Committee for Atmospheric Sciences (ICAS). The ICAS, established in 1959 by the former Federal Council for Science and Technology, provides advice on matters related to atmospheric science in general and has also been the principal coordinating mechanism for Federal research in weather modification.

In 1958 the National Science Foundation was designated lead agency for Federal weather modification research by Public Law 85-510, a role which it maintained until 1968, when Public Law 90-407 removed this responsibility from NSF. No further action was taken to name a lead agency, although there have been numerous recommendations to designate such a lead agency, and several bills introduced in the Congress would have named either the Department of the Interior or the Department of Commerce in that role. During the 10-year period from 1958 to 1968 the NSF promoted a vigorous research program through grants to various research organizations, established an Advisory Panel for Weather Modification, and published a series of 10 annual reports on weather modification activities in the United States. Since 1968 there has been a lapse in Federal weather modification policy and in the Federal structure for research programs, although, after a hiatus of over 3 years, the responsibility for collecting and disseminating information on weather modification activities was assigned to the Commerce Department in 1971. An important consideration of any future weather modification legislation will probably be the organizational structure of the Federal research program and that for administration of other related functions which may be the responsibility of the Federal Government. Options include a continuation of the present mission-oriented approach with coordination through the ICAS or a similar interagency body, redesignation of a lead agency with some autonomy remaining with the several agencies, or creation of a single agency with control of all funding and all research responsibilities. The latter could be an independent agency or part of a larger department; it would presumably also administer other aspects of Federal weather modification responsibilities, such as reporting of activities,

regulation and licensing, and monitoring and evaluation of operations, if any or all of these functions should become or continue to be services performed at the Federal level.

In addition to specific research programs sponsored by Federal agencies, there are other functions related to weather modification which are performed in several places in the executive branch. Various Federal advisory panels and committees and their staffs—established to conduct in-depth studies and prepare comprehensive reports, to provide advice and recommendations, or to coordinate Federal weather modification programs—have been housed and supported within executive departments, agencies, or offices. The program whereby Federal and non-Federal U.S. weather modification activities are reported to the Government is administered by the National Oceanic and Atmospheric Administration (NOAA) within the Commerce Department. The State Department negotiates agreements with other nations which might be affected by U.S. experiments and has arranged for Federal agencies and other U.S. investigators to participate in international meteorological projects, including those in weather modification. In the United Nations, the United States has been active in promoting the adoption of a treaty banning weather modification as a military weapon.

In accordance with the mandates of several public laws or self-initiated by the agencies or interagency committees, the executive branch of the Federal Government has undertaken a number of major weather modification policy studies over the past 25 years. Each of the completed major studies was followed by a report which included findings and recommendations. The most recent study is the one noted earlier that is being conducted by the Weather Modification Advisory Board on behalf of the Secretary of Commerce, pursuant to requirements of the National Weather Modification Policy Act of 1976. Nearly all previous studies emphasized the needs for designation of a lead agency, increased basic meteorological research, increased funding, improvement of support and cooperation from agencies, and consideration of legal, socioeconomic, environmental, and international aspects. Other recommendations have included improvement of program evaluation, study of inadvertent effects, increased regulation of activities, and a number of specific research projects. Although some of the recommended activities have been undertaken, many have not resulted in specific actions to date. Almost invariably it was pointed out in the studies that considerable progress would result from increased funding. Although funding for weather modification research has increased over the past 20 years, most funding recommendations have been for considerably higher levels than those provided. Since fiscal year 1976, the total Federal research funding for weather modification research has, in fact, decreased.

Most States in the Nation have some official interest in weather modification; 29 of them have some form of law which relates to such activities, usually concerned with various facets of regulation or control of operations within the State and sometimes pertaining to authorization for funding research and/or operations at the State or local level. A State's weather modification law usually reflects its general policy toward weather modification; some State laws tend to en-

courage development and use of the technology, while others discourage such activities.

The current legal regime regulating weather modification has been developed by the States rather than the Federal Government, except in the areas of research support, commissioning studies, and requiring reporting of activities. The various regulatory and management functions which the States perform include: (1) issuance, renewal, suspension, and revocation of licenses and permits; (2) monitoring and collecting of information on activities through requirements to maintain records, submission of periodic activity reports, and inspection of premises and equipment; (3) funding and managing of State or locally organized operational and/or research programs; (4) evaluation and advisory services to locally organized public and private operational programs within the State; and (5) miscellaneous administrative activities, including the organization and operation of State agencies and boards which are charged with carrying out statutory responsibilities. Administration of the regulatory and managerial responsibilities pertaining to weather modification within the States is accomplished through an assortment of institutional structures, including departments of water or natural resources, commissions, and special governing or advisory groups. Often there is a combination of two or more of these agencies or groups in a State, separating functions of pure administration from those of appeals, permitting, or advisory services.

Involvement in weather modification operational and research programs varies from State to State. Some support research only, while others fund and operate both research and operational programs. In some cases funding only is provided to localities, usually at the county level, where operational programs have been established. The recent 1976-77 drought led some Western States to initiate emergency cloud-seeding programs as one means of augmenting diminishing water supplies. Research conducted by atmospheric and other scientists at State universities or other research agencies may be supported in part with State funds but is often funded by one of the major Federal weather modification programs, such as that of the Bureau of Reclamation or the National Science Foundation. In a few cases, States contribute funds to a Federal research project which is conducted jointly with the States and partly within their borders.

In 1975, 1976, and 1977, respectively, there were 58, 61, and 88 non-federally supported weather modification projects, nearly all operational, conducted throughout the United States. These projects were sponsored by community associations, airlines, utilities, private interests, municipal districts, cities, and States. Eighty-five percent of all projects in the United States during 1975 were carried out west of Kansas City, with the largest number in California. In that State there were 11 projects in each of the years 1975 and 1976, and 20 projects during 1977. The majority of these operational projects were designed to increase precipitation; others were intended for suppression of hail or dispersal of fogs, the latter principally at airports.

In most instances, the principal beneficiaries of weather modification are the local or regional users, who include farmers and ranchers, weather-related industries, municipalities, airports, and utilities—

those individuals and groups whose economic well-being and whose lives and property are directly subject to adverse consequences of drought or other severe weather. It is at the local level where the need to engage in weather modification is most keenly perceived and also where possible negative effects from such activities are most apparent to some sectors of the population. It follows that both the greatest support and the strongest opposition to weather modification projects are focussed at the local level. The popularity of a particular project and the degree of controversy surrounding it are frequently determined by the extent to which local citizens and local organizations have had a voice in the control or funding of the project. At the local level, decisions to implement or to withdraw from a project can most often be made with minimum social stress. Indeed, studies have shown that most people are of the opinion that local residents or local government officials should make decisions on whether or not to use weather modification technology in a given situation.

Many of the operational weather modification services provided for private groups and governmental bodies within the States are carried out under contract by commercial firms who have developed expertise in a broad range of capabilities or who specialize in particular services essential to both operational or research projects. Contracts may cover only one season of the year, but a number of them are renewed annually, with target areas ranging from a few hundred to a few thousand square miles. In 1976, 6 of the 10 major companies having substantial numbers of contracts received about \$2.7 million for operations in the United States, and a few of these companies also had contracts overseas. Owing to increased demand for emergency programs during the recent drought, it is estimated that 1977 contracts totaled about \$3.5 million.

The initial role of the private weather modification operators was to sustain activities during the early years, when there was often heated scientific controversy with other meteorologists over the efficacy of cloud seeding. Later, their operations provided a valuable data base which permitted the early evaluation of seeding efforts and estimates of potential prospects for the technology, meanwhile growing in competence and public respect. Today, more often than not, they work hand in hand with researchers and, in fact, they often participate in research projects, contributing much of their knowhow acquired through their unique experiences.

Important among private institutions concerned with weather modification are the professional organizations of which research and operational weather modifiers and other interested meteorologists are members. These include the American Meteorological Society, the Weather Modification Association, and the Irrigation and Drainage Division of the American Society of Civil Engineers. Through the meetings and publications of these organizations the scientific, technical, and legal problems and findings on weather modification are aired and discussed. These groups also address other matters such as statements of weather modification policy, opinions on pending legislation, social implications, and professional standards and certification. In addition, the North American Interstate Weather Modification Council is an organization whose membership consists of govern-

ments of U.S. States and Canadian Provinces and the Government of Mexico, which serves as a forum for interstate coordination and exchange of information on weather modification.

Weather modification is often controversial, and both formal and informal opposition groups have been organized in various sections of the country. Reasons for such opposition are varied and are based on both real and perceived adverse consequences from weather modification. Sometimes with little or no rational basis there are charges by these groups that otherwise unexplained and usually unpleasant weather-related events are linked to cloud seeding. There are also cases where some farmers are economically disadvantaged through receiving more, or less than optimum rainfall for their particular crops, when artificial inducement of such conditions may have indeed been planned to benefit those growing different crops with different moisture requirements. Opposition groups are often formed to protect the legitimate rights of farmers under such circumstances.

While the United States is the apparent leader in weather modification research and operations, other countries have also been active. Information on foreign weather modification activities is not uniformly documented and is not always available. In an attempt to assemble uniform weather modification activities information of its member nations, the World Meteorological Organization (WMO) in 1975 instigated a system of reporting and of maintaining a register on such activities. Under this arrangement 25 nations reported weather modification projects during 1976, and 16 countries provided similar information in 1975. The largest weather modification effort outside the United States is in the Soviet Union, where there are both a continuing research program and an expanding operational program. The latter is primarily a program designed to reduce crop damage from hail, the largest such effort in the world, covering about 5 million hectares (15 million acres) in 1976. Other countries with weather modification programs of some note include Canada, Israel, Mexico, and the People's Republic of China. Projects in Rhodesia and the Republic of South Africa are not reported through the WMO register since these countries are not WMO member nations.

Recent years have seen increased international awareness of the potential benefits and possible risks of weather modification technology and increased international efforts to control such activities. The major efforts of the international community in this area are to encourage and maintain the high level of cooperation which currently exists in weather prediction and research and to insure that man's new abilities will be used for peaceful purposes. There has been exchange of ideas on weather modification through international conferences and through more informal exchanges of scientists and research documents. As with many scientific disciplines, however, the problems arising from use of and experiments with weather modification are not just scientific in nature, but are political problems as well.

In addition to the problems of potential damage to countries through commercial or experimental weather modification activities, another growing area of concern is that weather modification will be used for hostile purposes and that the future will bring weather warfare between nations. The United States has already been involved in one

such instance during the Vietnam war when attempts were made to impede traffic by increasing rainfall during the monsoon season. In the future, even the perception that weather modification techniques are available or in use could lead to an increase in international tensions. Natural drought in a region, or any other natural disaster will be suspect or blamed on an enemy.

In light of these problems the international community has made scattered attempts both to further the study of weather and its modification and to insure the peaceful use of this new technology. One such attempt was the development of the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, which was adopted by the General Assembly of the United Nations and opened for signature on May 18, 1977, at which time it was signed by the United States and 33 other nations (though it has not yet been submitted to the U.S. Senate for ratification). Another example of promotion of peaceful use of weather modification is the Precipitation Enhancement Program, sponsored by the WMO, whose aim is to plan, set up, and carry out an international, scientifically controlled precipitation experiment in a semiarid region of the world under conditions where the chances are optimal for increasing precipitation in sufficient amounts to produce economic benefits.

The United Nations Conference on the Human Environment, held in June 1972 in Stockholm, has been the pivotal point in much recent international environmental activity. It too has been an important catalyst in international activities relating to weather modification through portions of its "Declaration," its "Action Plan for the Human Environment," its "Earthwatch Program," and its "Study of Man's Impact on Climate."

Legal issues in weather modification are complex and unsettled. They can be considered in at least four broad categories: private rights in the clouds, liability for weather modification, interstate legal issues, and international legal issues. Since the body of law on weather modification is slight, existing case law offers few guidelines to determine these issues. Regarding the issue of private rights in the clouds, there is no general statutory determination of ownership of atmospheric water, so it is often necessary to use analogies to some general common law doctrines pertaining to water distribution, although each such doctrine has its own disadvantages when applied to weather modification. Some State laws reserve ownership or right to use atmospheric water to the State.

Issues of liability for damage may arise when drought, flooding, or other severe weather phenomena occur following attempts to modify the weather. Such issues include causation, nuisance, strict liability, trespass, negligence, and charges of pollution of the air and water through introduction of artificial nucleants. Statutes of 10 States discuss weather modification liability; however, there is much variation among the specific provisions of the laws in those States. Before a case can be made for liability based on causation, it must be proven that the adverse weather conditions were indeed induced by the weather modifier; but, in fact, no one has ever been able to establish causation of damages through such activities in view of the scientific uncertainties of weather modification.

Significant issues may arise when weather modification activities conducted in one State affect another State as well. There may be, for example, the claim that seeding in one State has removed from the clouds water that should have fallen in an adjacent State or that excessive flooding resulted from cloud seeding in a State upwind. Operation of cloud-seeding equipment near the border of one State may also violate local or State regulations or prohibitions of such operations in that State. There have been some attempts to resolve these and other issues through specific legislation in some States and through informal bilateral agreements. While no formal compacts currently exist, some compacts allocating waters in interstate streams may be applicable.

Because atmospheric processes operate independent of national borders, weather modification is inherently of international concern, and, international legal issues have similarities to domestic interstate activities and dangers. Whereas domestic weather modification law is confused and unsettled, international law in this area is barely in the formative stage. In time, ramifications of weather modification may lead to major international controversy.

Whereas the potential for long-term economic gains through weather modification cannot be denied, current economic analyses are tenuous in view of present uncertainty of the technology and the complex nature of attendant legal and economic problems. Economic evaluation of weather modification activities has therefore been limited to special, localized cases, such as the dispersal of cold fog at airports, where benefit-cost ratios greater than 5 to 1 have been realized through savings in delayed or diverted traffic. It has also been estimated, on the basis of a 15-percent increase in snowpack through seeding orographic clouds, that about 2 million additional acre-feet of water per year could be produced in the Colorado River Basin, at a cost of about \$1.50 per acre-foot.

Costs of most weather modification operations are generally small in relation to other costs in agriculture, for example, and are normally believed to be only a fraction of the benefits which could be achieved from successful operations. However, if all the benefits and all the costs are considered, benefit-cost ratios may be diminished. While direct costs and benefits from weather modification are reasonably apparent, indirect costs and benefits are elusive and require further study of sociological, legal, and ecological implications.

There are numerous cases of both real and perceived economic losses which one or more sectors of the public may suffer while another group is seeking economic advantage through some form of weather modification. Overall benefits from weather modification are accordingly reduced when net gains are determined from such instances of mixed economic advantages and disadvantages. In fact, when mechanisms are established for compensating those who have suffered losses resulting from weather modification, benefits to those groups seeking economic gain through such projects will probably be accordingly reduced.

Economically significant weather modification activities will have an eventual ecological effect, though appearance of that effect may be hidden or delayed by system resilience and/or confused by system

complexity. Prediction of ecological effects may never be possible with any precision; however, the greater the precision with which the weather modifier can predict results of his activities, the more precisely can the ecologist predict ecological effects. Such effects will rarely be sudden or catastrophic, but will result from moderate weather-related shifts in rates of reproduction, growth, and mortality of plants and animals. Adjustments of plant and animal communities will thus occur more slowly in regions of highly variable weather than in those with more uniform conditions which are slowly changing with some regularity over time. Deliberate weather modification, such as precipitation augmentation, is likely to have a greater ecological impact in semi-arid regions than in humid ones.

Widespread cloud seeding, using silver iodide, could result in estimated local, temporary increases in silver concentrations in precipitation approaching those in natural waters, but exchange rates would be an order of magnitude lower than the natural exchange rates. Exchange rates will likely be many orders of magnitude less than those rates at which plants and soils are adversely affected.

Conclusions

1. Weather modification is an emerging technology; there is a wide spectrum of capabilities to modify various weather phenomena, ranging from the operational readiness of cold fog dispersal to little progress beyond initial research in the case of modifying severe storms such as hurricanes.

2. Along with cold fog dispersal, the only other weather modification capability showing near readiness for application is the augmentation of winter snowpack through seeding mountain cloud systems. A probable increase of about 15 percent is indicated by a number of experiments and longrunning operational seeding projects in the western United States.

3. Most scientists and weather modification operators agree that there is continued need for a wide range of research and development activity both to refine weather modification techniques where there has been some success and to advance capabilities in modifying other weather phenomena where there has been much less or little progress.

4. Current Federal policy for weather modification research and development follows the mission-oriented approach, where each agency charged with responsibility for dealing with a particular national problem is given latitude to seek the best approach or solution to the problem; this approach or solution may involve weather modification.

5. The structure of Federal organization for weather modification reflects the mission-oriented approach which is characteristic of the current Federal policy, the programs loosely coordinated through advisory groups and the Interdepartmental Committee for Atmospheric Sciences.

6. The interest of the Congress in weather modification has been shown by the introduction of 110 bills related to the subject since 1947—6 of which have become public law—and the consideration of 22 resolutions on weather modification, one of which was passed by the Senate.

7. A number of major weather modification policy studies have been directed by public law or initiated within the executive branch over

the past 25 years; most of these studies recommended designation of a lead agency, increased basic meteorological research, increased funding, improvement of support and cooperation from agencies, and consideration of legal, socioeconomic, environmental, and international aspects. Although some recommended actions have been undertaken, others have not seen specific action to date.

8. While major policy studies have recommended increased funding for Federal weather modification, research and development and funding has generally increased over the past 20 years, recommended levels have been consistently higher than those provided, and funding has actually decreased since fiscal year 1976.

9. With enactment of the National Weather Modification Policy Act of 1976 and completion of the major policy study mandated by that act, there is a fresh opportunity for the Congress to assess the potential usefulness and problems in application of weather modification technology and to establish a new Federal policy for weather modification research and operations.

10. The principal role in regulating weather modification and in supporting operational programs has been taken by the States, while the role of the Federal Government has been support of research and development programs.

11. The majority of the States (29) have some form of law which relates to weather modification, and the general policy of a State toward weather modification is usually reflected in the weather modification law of that State; laws of some States tend to encourage development and use of the technology, while others discourage such activities.

12. The majority of operational weather modification projects in the United States (58 of a total of 72, or 80 percent in calendar year 1975) are conducted west of Kansas City, and the largest number of projects has been in California (20 during 1977); most operational projects are intended to increase precipitation, while others are designed to suppress hail or disperse fog.

13. Both the greatest support and the strongest opposition to weather modification projects are focused at the local level, where the economic and personal interests of local organizations and individuals are most directly affected; it follows that there is also the least social stress when decisions to apply or withhold weather modification are made at the local level.

14. Commercial weather modification operators have sustained activities since the early days, after which some operations fell into disrepute, providing a valuable data base for evaluation of long-term projects and developing expertise over a broad range of capabilities; most have incorporated improvements into their technology as they have benefited from accumulated experience and from research results.

15. While the United States is the apparent leader in overall research and operational weather modification activities, there have been approximately 20 foreign countries in which activities are conducted annually (25 countries reported such projects for 1976 through the register of the World Meteorological Organization); the largest foreign program is that of the Soviet Union, whose operational hail suppression program covered about 15 million acres in 1976, the largest such effort in the world.

16. The international community has attempted to further the study of weather modification and insure its peaceful use through the recent development of a Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Techniques (adopted by the U.N. General Assembly and opened for signature in May 1977) and through sponsorship by the World Meteorological Organization of an international precipitation enhancement program.

17. Legal issues in weather modification are complex and unsettled; they include resolution of problems of ownership of atmospheric water, issues of liability, conflicting statutes and regulations of respective State laws, and the need to develop a regime of relevant international law.

18. Although the long-term potential for economic gains through weather modification cannot be denied, attempts to quantify benefits and costs from such activities will in most cases be difficult to undertake on a practical basis until the technology is more highly developed and control systems are perfected to permit reliable predictions of outcomes.

19. Economically significant weather modification will always have an eventual ecological effect, though appearance of the effect may be delayed or hidden by system resilience and/or confounded by system complexity; the more precisely the weather modifier can specify effects he will produce, the more precise can be the ecologist's prediction of likely ecological effects.

20. Modification processes may also be initiated or triggered inadvertently rather than purposefully; man is already causing measurable variations unintentionally on the local scale, and artificial climate effects have been observed on local and regional scales. Although not verifiable at present, the time may not be remote when human activities will result in measurable large-scale changes in weather and climate of more than passing significance.

CHAPTER 1

INTRODUCTION AND SUMMARY OF ISSUES

(By Robert E. Morrison, Specialist in Earth Sciences, Science Policy Research Division, Congressional Research Service)

PERSPECTIVE

"It is entirely possible, were he wise enough, that man could produce favorable effects, perhaps of enormous practical significance, transforming his environment to render it more salutary for his purposes. This is certainly a matter which should be studied assiduously and explored vigorously. The first steps are clear. In order to control meteorological matters at all we need to understand them better than we now do. When we understand fully we can at least predict weather with assurance for reasonable intervals in the future.

"With modern analytical devices, with a team of sound background and high skills, it is possible today to do a piece of work in this field which will render immediate benefits, and carry us far toward a more thorough understanding of ultimate possibilities. By all means let us get at it."

—Vannevar Bush ¹

SITUATION

Two decades after completion of a major study and report on weather modification by the Advisory Committee on Weather Control and after the assertions quoted above, many would agree that some of the more fundamental questions about understanding and using weather modification remain unsolved. There is a great difference of opinion, however, on the state of technology in this field. According to Grant, "Some believe that weather modification is now ready for widespread application. In strong contrast, others hold that application of the technology may never be possible or practical on any substantial scale."² It has been demonstrated that at least some atmospheric phenomena can be modified with some degree of predictable success, as a consequence of seeding supercooled clouds with artificial ice nuclei, and there is some promise that the present technology will be expanded to include a greater scope of weather modification capabilities. Nevertheless, a systematic approach and reasonable progress in development of weather modification technology have been impeded by a number of problems.

Changnon asserts that a continuing and overriding problem restricting progress has been the attempt to apply an ill-defined technology to increase rain or suppress hail without an adequate scientific under-

¹ From statement of Dec. 2, 1957, quoted in final report of the Advisory Committee on Weather Control, Washington, D.C., U.S. Government Printing Office, 1958, vol. I, p. 1.

² Grant, Lewis O., "Scientific and Other Uncertainties of Weather Modification." In William A. Thomas (editor), *Legal and Scientific Uncertainties of Weather Modification*, Proceedings of a symposium convened at Duke University, Mar. 11-12, 1976, by the National Conference of Lawyers and Scientists, Durham, N.C., Duke University Press, 1977, p. 7.

standing and predictable outcome.³ Experimentation has been poorly conducted, intermittent, or too short; and "results have not been integrated with those of other projects so as to develop a continuing thread of improving knowledge."⁴

In response to the query as to why progress in weather modification has been so slow, Fleagle identifies three broad, general impediments. "First, the physical processes associated with clouds have turned out to be especially complex and difficult * * *. A second possibility may be that the atmosphere is inherently stable, so that within broad limits, no matter what we do to increase precipitation, the results are likely to be small and roughly the same * * *. A third reason * * * is that progress has been hamstrung by fragmentation of resources, by submarginal funding, ineffective planning and coordination, and a general lack of administrative toughness and fiscal stability."⁵

Droessler points out the need to "formulate a comprehensive national weather modification policy which has the broad support of the scientific community, the general public, private industry, and the Government," contending that "the greatest deterrent in getting on with the task of preparing a satisfactory national policy is the lack of a consensus about the national goals for weather modification."⁶

Although operational readiness varies from one form of weather modification to another, as a result of the degree of understanding and the complexity of decisionmaking in given situations, the prospects for successful weather modification are sufficiently promising that attempts to develop effective applications will continue. This was one of the major areas of consensus at a recent symposium on the uncertainties of weather modification:

There will be increased attempts to modify weather, both because people tend to do what is technically possible and because the anticipated benefits of precipitation augmentation, hail or lightning suppression, hurricane diversion, and other activities often exceed the associated costs.⁷

With the inevitable increases in weather modification capabilities and the increasing application of these capabilities, the development of a technology that is socially useful must be insured through a careful analysis of attendant benefits and disbenefits. According to Fleagle, et al., deliberate efforts to modify the weather have thus far had only marginal societal impacts; however, as future activities expand, "they will probably be accompanied by secondary effects which in many instances cannot be anticipated in detail * * *." Consequently, "rational policy decisions are urgently needed to insure that activities are directed toward socially useful goals."⁸

The lack of a capability to deal with impending societal problems

³ Changnon, Stanley A., Jr., "The Federal Role in Weather Modification," background paper prepared for use by the U.S. Department of Commerce Weather Modification Advisory Board, Mar. 9, 1977, p. 5.

⁴ *Ibid.*, pp. 5-6.

⁵ Fleagle, Robert G., "An Analysis of Federal Policies in Weather Modification," background paper prepared for use by the U.S. Department of Commerce Weather Modification Advisory Board, Mar. 1977, pp. 17-18.

⁶ Droessler, Earl G., "Weather Modification" (Federal Policies, Funding From All Sources, Interagency Coordination), background paper prepared for use of the U.S. Department of Commerce Weather Modification Advisory Board, Mar. 1, 1977, p. 10.

⁷ Thomas, William A. (editor), "Legal and Scientific Uncertainties of Weather Modification," proceedings of a symposium convened at Duke University, Mar. 11-12, 1976, by the National Conference of Lawyers and Scientists, Durham, N.C., Duke University Press, 1977, p. vi.

⁸ Fleagle, Robert G., James A. Crutchfield, Ralph W. Johnson, and Mohamed F. Abdo, "Weather Modification in the Public Interest," Seattle, American Meteorological Society and the University of Washington Press, 1973, p. 3, 31-32.

and emerging management issues in weather modification has been aphoristically summed up in the following statement by Crutchfield:

Weather modification is in the throes of a serious schizoid process. The slow and sober business of piecing together the scientific knowledge of weather processes, developing the capacity to model the complex systems involved, and assessing systematically the results of modification efforts has led to responsible optimism about the future of these new technologies. On the other hand, the "social technology" of evaluation, choice, and execution has lagged badly. The present decisionmaking apparatus appears woefully inadequate to the extraordinarily difficult task of fitting weather modification into man's pattern of life in optimal fashion. There are too many game plans, too many coaches, and a disconcerting proclivity for running hard before deciding which goal line to aim for—or, indeed, which field to play on.

Mounting evidence indicates that weather modification of several types is, or may soon become technically feasible. That some groups will derive economic or other social benefits from such technology is a spur to action. But a whole thunderhead of critical questions looms on the horizon waiting to be resolved before any valid decisions can be made about the scale, composition, location, and management of possible operations.⁹

ADVANTAGES

In a study for the Interdepartmental Committee for Atmospheric Sciences, Homer E. Newell highlighted the potential benefits of intentional weather modification:

The Earth's weather has a profound influence on agriculture, forestry, water resources, industry, commerce, transportation, construction, field operations, commercial fishing, and many other human activities. Adverse effects of weather on man's activities and the Earth's resources are extremely costly, amounting to billions of dollars per year, sometimes causing irreparable damage as when human lives are lost in severe storms. There is, therefore, great motivation to develop effective countermeasures against the destructive effects of weather, and, conversely, to enhance the beneficial aspects. The financial and other benefits to human welfare of being able to modify weather to augment water supplies, reduce lightning, suppress hail, mitigate tornadoes, and inhibit the full development of hurricanes would be very great.¹⁰

More recently, Louis J. Battan gave the following two reasons, with graphic examples, for wanting to change the weather:

First, violent weather kills a great many people and does enormous property damage. A single hurricane that struck East Pakistan in November 1970 killed more than 250,000 people in a single day. Hurricane Camille hit the United States in 1969 and did approximately \$1.5 billion worth of damage. An outbreak of tornadoes in the Chicago area on Palm Sunday of 1965 killed about 250 people, and the tornadoes of April 1974 did likewise. Storms kill people and damage property, and it is reasonable to ask whether it is necessary for us to accept this type of geophysical destruction. I say, "No, it is not—it should be possible to do something."

Second, weather modification involves, and in some respects might control, the production of those elements we need to survive. Water and food are currently in short supply in many areas, and these shortages almost certainly will be more severe in the future. We can develop new strains of wheat and rye and corn and soybeans and rice, but all is for naught if the weather fails to cooperate. If the monsoons do not deliver on schedule in India, residents of that country starve in large numbers. And if the drought that people have been predicting for the last several years does spread over the Great Plains, there will be starvation around the world on a scale never before experienced.

Weather is the one uncontrollable factor in the whole business of agriculture. Hail, strong winds, and floods are the scourges of agriculture, and we should not have to continue to remain helpless in the face of them. It may be impossible

⁹ Crutchfield, James A. "Social Choice and Weather Modification: Concepts and Measurement of Impact." In W. R. Derrick Sewell (editor). *Modifying the Weather: a Social Assessment*, Victoria, British Columbia, University of Victoria, 1973, p. 187.

¹⁰ Newell, Homer E., "A Recommended National Program in Weather Modification." Federal Council for Science and Technology, Interdepartmental Committee for Atmospheric Sciences, ICAS report No. 10a, Washington, D.C., November 1966, p. 1.

for us to develop the kind of technology we would like to have for modification of weather, but to assume failure in such an important endeavor is a course not to be followed by wise men.¹¹

Specific statistics on annual losses of life and economic losses from property damages resulting from weather-related disasters in the United States are shown in table 1, which was developed in a recent study by the Domestic Council.¹² In the table, for comparison, are the fiscal year 1975 expenditures by the Federal Government in weather modification research, according to the several categories of weather phenomena to be modified. Although it is clear that weather disasters can be mitigated only partially through weather modification, even if the technology were fully developed, the potential value, economic and otherwise, should be obvious. The following quotation from a Federal report written over a decade ago summarizes the full potential of benefits to mankind which might be realized through use of this technology:

With advances in his civilization, man has learned how to increase the fruit of the natural environment to insure a livelihood. * * * it is fortunate that growing knowledge of the natural world has given him an increasing awareness of the changes that are occurring in his environment and also hopefully some means for deliberate modification of these trends. An appraisal of the prospects for deliberate weather and climate modification can be directed toward the ultimate goal of bringing use of the environment into closer harmony with its capacities and with the purposes of man—whether this be for food production, relief from floods, assuring the continuance of biologic species, stopping pollution, or for purely esthetic reasons.¹³

TABLE 1.—ANNUAL PROPERTY DAMAGE AND LOSS OF LIFE FROM WEATHER-RELATED DISASTERS AND HAZARDS IN THE UNITED STATES AND FISCAL YEAR 1975 FEDERAL WEATHER MODIFICATION RESEARCH FUNDING (FROM DOMESTIC COUNCIL REPORT, 1975)

Weather hazard	Loss of life ¹	Property damage ¹ (billions)	Modification research (millions)
Hurricanes.....	2 30	2 \$0.8	2 \$0.8
Tornadoes.....	2 140	2.4	4 1.0
Hail.....		5.8	3.9
Lightning.....	6 110	.1	.4
Fog.....	7 1,000	7.5	1.3
Floods.....	8 240	8 2.3	---
Frost (agriculture).....		7 1.1	---
Drought.....		7.7	9 3.4
Total.....	1,520	6.7	10.8

¹ Sources: "Assessment of Research on Natural Hazards," Gilbert F. White and J. Eugene Haas, the MIT Press, Cambridge, Mass., 1975, pp 68, 286, 305, 374; "The Federal Plan for Meteorological Services and Supporting Research, Fiscal Year 1976," U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), Washington, D.C., April 1975, p 9; "Weatherwise," February 1971, 1972, 1973, 1974, 1975, American Meteorological Society, Boston, Mass.; "Summary Report on Weather Modification, Fiscal Years 1969, 1970, 1971," U.S. Department of Commerce, NOAA, Washington, D.C., May 1973, pp 72, 81; "Estimating Crop Losses Due to Hail—Working Data for County Estimates," U.S. Department of Agriculture, Economic Research Service, September 1974; "Natural Disasters: Some Empirical and Economic Considerations," G. Thomas Sav, National Bureau of Standards, Washington, D.C., February 1974, p 19; Traffic Safety magazine, National Safety Council, February 1974.

² 1970–74 average.

³ These funds do not include capital investment in research aircraft and instrumentation primarily for hurricane modification, which in fiscal year 1975 amounted to \$9,200,000.

⁴ These funds support theoretical research on modification of extratropical cloud systems and their attendant severe storms such as thunderstorms and tornadoes.

⁵ 1973.

⁶ 1950–72 average.

⁷ Average.

⁸ 1965–69 average.

⁹ These funds support precipitation augmentation research, much of which may not have direct application to drought alleviation.

¹¹ Battan, Louis J., "The Scientific Uncertainties: a Scientist Responds." In William A. Thomas (editor), "Legal and Scientific Uncertainties of Weather Modification," proceedings of a symposium convened at Duke University, Mar. 11–12, 1976, by the National Conference of Lawyers and Scientists, Durham, N.C., Duke University Press, 1977, p. 26.

¹² U.S. Domestic Council, Environmental Resources Committee, Subcommittee on Climate Change, "The Federal Role in Weather Modification," December 1975, p. 2.

¹³ Special Commission on Weather Modification, "Weather and Climate Modification," National Science Foundation, NSF 66–3, Washington, D.C., Dec. 20, 1965, p. 7.

TIMELINESS

The modern period in weather modification is about three decades old, dating from events in 1946, when Schaefer and Langmuir demonstrated that a cloud of supercooled water droplets could be transformed into ice crystals when seeded with dry ice. Activities and interests among scientists, the commercial cloud seeders, and Government sponsors and policymakers have exhibited a nearly 10-year cyclic behavior over the ensuing years. Each of the three decades since the late 1940's has seen an initial burst of enthusiasm and activity in weather modification experiments and/or operations; a midcourse period of controversy, reservations, and retrenchment; and a final period of capability assessment and policy examination, with the issuance of major Federal reports with comprehensive recommendations on a future course.

The first such period ended with the publication of the final report of the Advisory Committee on Weather Control in 1957.¹⁴ In 1959, Dr. Robert Brode, then Associate Director of the National Science Foundation, summarized the significance of that study in a 1959 congressional hearing:

For 4 years the Advisory Committee studied and evaluated public and private cloud-seeding experiments and encouraged programs aimed at developing both physical and statistical evaluation methods. The final report of the committee * * * for the first time placed before the American public a body of available facts and a variety of views on the status of the science of cloud physics and the techniques and practices of cloud seeding and weather modification.¹⁵

The year 1966 was replete with Government weather modification studies, major ones conducted by the National Academy of Sciences, the Special Commission on Weather Modification of the National Science Foundation, the Interdepartmental Committee for Atmospheric Sciences, and the Legislative Reference Service of the Library of Congress. During that year, or thereabouts, planning reports were also produced by most of the Federal agencies with major weather modification programs. The significance of that year of reevaluation and the timeliness for congressional policy action were expressed by Hartman in his report to the Congress:

It is especially important that a comprehensive review of weather modification be undertaken by the Congress at this time, for a combination of circumstances prevails that may not be duplicated for many years. For the first time since 1957 there now exists, in two reports prepared concurrently by the National Academy of Sciences and a Special Commission on Weather Modification, created by the National Science Foundation, a definitive appraisal of the entire scope of this subject, the broad sweep of unsolved problems that are included, and critical areas of public policy that require attention. There are currently before the Congress several bills which address, for the first time since enactment of Public Law 85-510, the question of the formal assignment of Federal authority to undertake weather modification programs. And there is increasing demand throughout the country for the benefits that weather modification may bring.¹⁶

¹⁴ Establishment of the Advisory Committee on Weather Control by the Congress and its activities are discussed in following chapters on the history of weather modification and on Federal activities, chs. 2 and 5, respectively. Recommendations of the final report are summarized in ch. 6. Other reports mentioned in the following paragraphs in this section are also discussed and referenced in chs. 5 and 6.

¹⁵ U.S. Congress, House of Representatives, Committee on Science and Astronautics, "Weather Modification," Hearing, 86th Cong., 1st sess., Feb. 16, 1959, Washington, D.C., U.S. Government Printing Office, 1959, p. 3.

¹⁶ Hartman, Lawton M. "Weather Modification and Control." Library of Congress, Legislative Reference Service, Apr. 27, 1966. Issued as a committee print by the Senate Committee on Commerce, 89th Cong., 2d sess., Senate Rept. No. 1139, Washington, D.C., U.S. Government Printing Office, 1966, p. 1.

Toward the close of the third decade, a number of policy studies and reports appeared, starting in 1973 with a second major study by the National Academy of Sciences, and including others by the U.S. General Accounting Office and by the U.S. Domestic Council. The major study of this period was commissioned by the Congress when it enacted Public Law 94-490, the National Weather Modification Policy Act of 1976, in October of 1976. By that law the Secretary of Commerce was directed to conduct a study and to recommend the Federal policy and a Federal research program in weather modification. That study was conducted on behalf of the Secretary of Commerce by a Weather Modification Advisory Board, appointed by the Secretary, and the required report will be transmitted to the Congress during 1978. The importance of that act and its mandated study was assessed by Dr. Robert M. White, former Administrator of the National Oceanic and Atmospheric Administration (NOAA), the Commerce Department agency with administrative responsibilities and research programs in weather modification:

The National Weather Modification Policy Act of 1976 * * * will influence NOAA to some degree during the next year, and its effect may have a large impact on the agency and the Nation in future years. The comprehensive study of and report on weather modification that will result from our implementation of this act will provide guidance and recommendations to the President and the Congress in the areas of policy, research, and utilization of this technology. We look to this study and report as an opportunity to help set the future course of a controversial science and technology with enormous potential for benefit to the Nation.¹⁷

Thus, conditions once more are ripe and the stage has been set, as in 1957 and again in 1966, for the Congress to act in establishing a definitive Federal weather modification policy, one appropriate at least for the next decade and perhaps even longer. Among other considerations, such a policy would define the total role of the Federal Government, including its management structure, its responsibilities for research and development and for support operations, its authorities for regulation and licensing, its obligation to develop international cooperation in research and peaceful applications, and its function in the general promotion of purposeful weather modification as an economically viable and socially accepted technology. On the other hand, other factors, such as constraints arising from public concern over spending, may inhibit the development of such policy.

While some would argue that there exists no Federal policy, at least one White House official, in response to a letter to the President, made a statement of weather modification policy in 1975:

A considerable amount of careful thought and study has been devoted to the subject of weather modification and what the Federal role and, in particular, the role of various agencies should be in this area. As a result of this study, we have developed a general strategy for addressing weather modification efforts which we believe provides for an appropriate level of coordination.

We believe that the agency which is charged with the responsibility for dealing with a particular national problem should be given the latitude to seek the best approach or solution to the problem. In some instances this may involve a form of weather modification, while in other instances other approaches may be more appropriate.

While we would certainly agree that some level of coordination of weather modification research efforts is logical, we do not believe that a program under

¹⁷ U.S. Congress, House of Representatives, Committee on Science and Technology. Subcommittee on the Environment and the Atmosphere. "Briefing on the National Oceanic and Atmospheric Administration." Hearings, 95th Cong., 1st sess., May 17, 18, 1977. Washington, U.S. Government Printing Office, 1977, p. 4-5.

the direction of any one single agency's leadership is either necessary or desirable. We have found from our study that the types of scientific research conducted by agencies are substantially different in approach, techniques, and type of equipment employed, depending on the particular weather phenomena being addressed. Each type of weather modification requires a different form of program management and there are few common threads which run along all programs.¹⁸

Presumably, there will be a resurgence of congressional interest in weather modification policy during the first session of the 96th Congress, when the aforementioned report from the Secretary of Commerce has been reviewed and considered. In view of the recommendations in numerous recent studies and the opinions of the Weather Modification Advisory Board (the group of experts preparing the report for the Secretary of Commerce), it seems unlikely that any action by the Congress would perpetuate the policy expounded in the White House letter quoted above.

It is expected that this present report, intended as an overall review of the subject of weather modification, will be valuable and timely during the anticipated congressional deliberations.

DEFINITIONS AND SCOPE OF REPORT

In the broadest sense, weather modification refers to changes in weather phenomena brought on purposefully or accidentally through human activity. Weather effects stimulated unintentionally—such as urban influences on rainfall or fogs produced by industrial complexes—constitute what is usually termed inadvertent weather modification. On the other hand, alterations to the weather which are induced consciously or intentionally are called planned or advertent weather modification. Such activities are intended to influence single weather events and to occur over relatively short time spans, ranging from a few hours in the case of clearing airport fog or seeding a thunderstorm to perhaps a few days when attempts are made to reduce the severity of hurricane winds. Weather modification experiments or operations can be initiated or stopped rather promptly, and changes resulting from such activities are transient and generally reversible within a matter of hours.

Climate modification, by contrast, encompasses changes of long-time climatic variables, usually affecting larger areas and with some degree of permanence, at least in the short term. Climatic changes are also brought about by human intervention, and they might result from either unintentional or planned activities. There are numerous examples of possible inadvertent climate modification; however, attempts to alter climate purposefully are only speculative. The concepts of inadvertent weather and climate modification are defined more extensively and discussed fully in chapter 4 of this report.

The primary emphasis of this report is on intentional or planned modification of weather events in the short term for the general benefit of people, usually in a restricted locality and for a specific time. Such benefit may accrue through increased agricultural productiv-

¹⁸ Ross, Norman E., Jr., letter of June 5, 1975, to Congressman Gilbert Gude. This letter was the official White House response to a letter of April 25, 1975, from Congressmen Gude and Donald M. Fraser and Senator Claiborne Pell, addressed to the President, urging that a coordinated Federal program be initiated in the peaceful uses of weather modification. The letter to the President, the reply from Mr. Ross, and comments by Congressman Gude appeared in the Congressional Record for June 17, 1975, pp. 19201-19203. (This statement from the Congressional Record appears in app. A.)

ity or other advantages accompanying augmentation of precipitation or they may result from mitigation of effects of severe weather with attendant decreases in losses of life or property. There are broader implications as well, such as the general improvement of weather for the betterment of man's physical environment for aesthetic and cultural reasons as well as economic ones. The following recent definition sums up succinctly all of these purposes:

Weather modification is the deliberate and mindful effort by men and women to enhance the atmospheric environment, to aim the weather at human purposes.¹⁹

The specific kinds of planned weather modification usually considered, and those which are discussed, in turn, in some detail in chapter 3, are the following:

Precipitation enhancement.

Hail suppression.

Fog dissipation.

Lightning suppression.

Mitigation of effects of severe storms.

Planned weather modification is usually considered in the context of its net benefits to society at large. Nevertheless, it should be recognized that, in particular instances, benefits to some segment of the population may be accompanied by unintended injuries and costs, which may be real or perceived, to other segments. There is yet another aspect of advertent weather modification, which has engendered much controversy, both in the United States and internationally, not designed for the benefit of those directly affected—the use of weather modification for hostile purposes such as a weapon of war. This aspect is not a major consideration in this report, although there is some discussion in chapters 5 and 10 of congressional concern about such use of the technology, and in chapter 10 there is also a review of recent efforts by the United Nations to develop a treaty barring hostile use of weather modification.²⁰

Following this introductory chapter, with its summary of issues, the second chapter sets the historical perspective for weather modification, concentrating primarily on activities in the United States to about the year 1970. The third chapter attempts to review the scientific background, the status of technology, and selected technical problems areas in planned weather modification; while chapter 4 contains a discussion of weather and climate changes induced inadvertently by man's activities or by natural phenomena.

The weather modification activities of the Federal Government—those of the Congress and the administrative and program activities of the executive branch agencies—are encompassed in chapter 5; and the findings and recommendations of major policy studies, conducted by or on behalf of the Federal Government, are summarized in chapter 6. The seventh, eighth, and ninth chapters are concerned with weather modification activities at the level of State and local governments, by private organizations, and in foreign countries, respectively.

¹⁹ Weather Modification Advisory Board, "A U.S. Policy to Enhance the Atmospheric Environment," Oct. 21, 1977. A discussion paper, included with testimony of Harlan Cleveland, Chairman of the Advisory Board, in a congressional hearing: U.S. Congress, House of Representatives, Committee on Science and Technology, Subcommittee on the Environment and the Atmosphere, Weather Modification, 95th Cong., 1st sess., Oct. 26, 1977, Washington, D.C., U.S. Government Printing Office, 1977, p. 25.

²⁰ Copies of the current official position of the U.S. Department of Defense on weather modification and of the draft U.N. convention prohibiting hostile use of environmental modification, respectively, are found in apps. B and C.

The increasingly important international problems related to weather modification are addressed in chapter 10, while both domestic and international legal aspects are discussed in chapter 11. Chapters 12 and 13, respectively, contain discussions on economic and ecological aspects of this emerging technology.

The 20 appendixes to the report provide materials that are both supplementary to textual discussions in the 13 chapters and intended to be valuable sources of reference data. In particular, attention is called to appendix D, which contains excerpts dealing with weather modification from the statutes of the 29 States in which such activities are in some way addressed by State law, and to appendix E, which provides the names and affiliations of individuals within the 50 States who are cognizant of weather modification activities and interests within the respective States. The reader is referred to the table of contents for the subjects of the remaining appendixes.

SUMMARY OF ISSUES IN PLANNED WEATHER MODIFICATION

"The issues we now face in weather modification have roots in the science and technology of the subject, but no less importantly in the politics of Government agencies and congressional committees and in public attitudes which grow out of a variety of historical, economic, and sociological factors."²¹ In this section there will be an identification of critical issues which have limited development of weather modification and which influence the ability to direct weather modification in a socially responsible manner. The categories of issues do not necessarily correspond with the subjects of succeeding chapters dealing with various aspects of weather modification; rather, they are organized to focus on those specific areas of the subject where there has been and there are likely to be problems and controversies which impede the development and application of this technology.

The following sections examine technological, governmental, legal, economic, social, international, and ecological issues. Since the primary concern of this report is with the intentional, planned use of weather modification for beneficial purposes, the issues summarized are those involved with the development and use of this advertent technology. Issues and recommendations for further research in the area of inadvertent weather modification are included in chapter 4, in which that general subject is fully discussed.

TECHNOLOGICAL PROBLEMS AND ISSUES

In a recent discussion paper, the Weather Modification Advisory Board summarized the state of weather modification by concluding that "no one knows how to modify the weather very well, or on a very large scale, or in many atmospheric conditions at all. The first requirement of a national policy is to learn more about the atmosphere itself."²² Representative of the state of weather modification science

²¹ Flegle, Crutchfield, Johnson, and Abdo, "Weather Modification in the Public Interest," 1973, p. 15.

²² Weather Modification Advisory Board. "A U.S. Policy To Enhance the Atmospheric Environment," Oct. 21, 1977. This discussion paper was included with the testimony of Mr. Harlan Cleveland, Chairman of the Advisory Board, in a recent congressional hearing: U.S. Congress, House of Representatives, Committee on Science and Technology, Subcommittee on the Environment and the Atmosphere, "Weather Modification," 95th Cong., 1st sess. Oct. 26, 1977, Washington, D.C., U.S. Govt. Print. Off., 1977, p. 25.

and technology is the following commentary on the state of understanding in the case of precipitation enhancement, or rainmaking as it is popularly called:

Today, despite the fact that modern techniques aimed at artificial stimulation of rain rest upon sound physical principles, progress is still fairly slow. The application of these principles is complicated by the overwhelming complexity of atmospheric phenomena. It is the same dilemma that meteorologists face when they attempt to predict weather. In both cases, predicting the evolution of atmospheric processes is limited by insufficient knowledge of the effects produced by the fairly well-known interactive mechanisms governing atmospheric phenomena. Moreover, the temporal and spatial variability of atmospheric phenomena presents an additional difficulty. Since any effects that are produced by artificial intervention are always imposed upon already active natural processes, assessment of the consequences becomes even more difficult.²³

Grant recognizes the current progress and the magnitude of remaining problems when he says that:

Important and steady advances have been made in developing technology for applied weather modification, but complexity of the problems and lack of adequate research resources and commitment retard progress. Advances have been made in training the needed specialists, in describing the natural and treated cloud systems, and in developing methodology and tools for the necessary research. Nevertheless, further efforts are required.²⁴

Though it can be argued that progress in the development of weather modification has been retarded by lack of commitment, ineffective planning, and inadequate funding, there are specific scientific and technical problems and issues needing resolution which can be identified beyond these management problems and the basic scientific problem quoted above with respect to working with the atmosphere. Particular technical problems and issues at various levels which continue to affect both research and operational activities are listed below:

1. There is substantial diversity of opinion, even among informed scientists, on the present state of technology for specific types of weather modification and their readiness for application and with regard to weather modification in general.²⁵

2. There are many who view weather modification only as a drought-relief measure, expecting water deficits to be quickly replenished through its emergency use; however, during such periods weather modification is limited by less frequent opportunities; it should, instead, be developed and promoted for its year-round use along with other water management tools.²⁶

3. The design and analysis of weather modification experiments is intimately related to the meteorological prediction problem, which needs further research, since the evaluation of any attempt to modify the atmosphere depends on a comparison between some weather parameter and an estimate of what would have happened naturally.

4. Many of the problems which restrict understanding and prediction of weather modification phenomena stem from imprecise knowledge of fundamental cloud processes; the level of research in funda-

²³ Dennis, Arnett S., and A. Gegin. "Recommendations for Future Research in Weather Modification." U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Boulder, Colo., November 1977, p. 12.

²⁴ Grant, "Scientific and Other Uncertainties of Weather Modification," 1977, p. 17.

²⁵ See table 2, ch. 3, p. 59.

²⁶ Silverman, Bernard A., "What Do We Need in Weather Modification?" In preprints of the Sixth Conference on Planned and Inadvertent Weather Modification, Oct. 10-13, 1977, Champaign, Ill., Boston, American Meteorological Society, 1977, p. 308.

mental cloud physics and cloud modeling has not kept pace with weather modification activity.²⁷

5. Progress in the area of weather modification evaluation methodology has been slow, owing to the complexity of verification problems and to inadequate understanding of cloud physics and dynamics.

6. Most operational weather modification projects, usually for the sake of economy or in the anticipation of achieving results faster and in greater abundance, fail to include a satisfactory means for project evaluation.

7. There are difficulties inherent in the design and evaluation of any experiment or operation which is established to test the efficacy of any weather modification technique, and such design requires the inclusion of proper statistical methods.

8. In view of the highly varying background of natural weather phenomena, statistical evaluation of seeding requires a sufficiently long experimental period; many research projects just barely fail to achieve significance and credibility because of early termination; thus, there is a need for longer commitment for such projects, perhaps 5 to 10 years, to insure that meaningful results can be obtained.²⁸

9. There is a need to develop an ability to predict possible adverse weather effects which might accompany modification of specific weather phenomena; for example, the extent to which hail suppression or diminishing hurricane winds might also reduce beneficial precipitation, or the possibility of increasing hailfall or incidence of lightning from efforts to stimulate rainfall from cumulus clouds.²⁹

10. The translation of cloud-seeding technologies demonstrated in one area to another geographical area has been less than satisfactory; this has been especially so in the case of convective cloud systems, whose differences are complex and subtle and whose classification is complicated and sometimes inconsistent.

11. There is increasing evidence that attempts to modify clouds in a prescribed target area have also induced changes outside the target area, resulting in the so-called downwind or extended area effect; reasons for this phenomenon and means for reducing negative results need investigation.

12. There is the possibility that cloud seeding in a given area and during a given time period has led to residual or extended time effects on weather phenomena in the target area beyond those planned from the initial seeding.

13. The conduct of independent cloud-seeding operations in adjacent locations or in the neighborhood of weather modification experiments may cause contamination of the atmosphere so that experimental results or estimates of operational success are biased.

14. There have been and continue to be conflicting claims as to the reliability with which one can conduct cloud-seeding operations so that the seeding agent is transported properly from the dispensing device to the clouds or portions of the clouds one seeks to modify.

²⁷ Hosler, C. L., "Overt Weather Modification." *Reviews of Geophysics and Space Physics*, vol. 12, No. 3, August 1974, p. 526.

²⁸ Simpson, Joanne, "What Weather Modification Needs." In preprints of the Sixth Conference on Planned and Inadvertent Weather Modification, Oct. 10-13, 1977, Champaign, Ill., Eston, American Meteorological Society, 1977, p. 306.

²⁹ Hosler, "Overt Weather Modification," 1974, p. 525.

15. There is need to develop, improve, and evaluate new and currently used cloud-seeding materials and to improve systems for delivery of these materials into the clouds.

16. There is need to improve the capability to measure concentrations of background freezing nuclei and their increase through seeding; there is poor agreement between measurements made with various ice nucleus counters, and there is uncertainty that cloud chamber measurements are applicable to real clouds.³⁰

17. In order to estimate amounts of fallen precipitation in weather modification events, a combination of weather radar and raingage network are often used; results from such measurement systems have often been unsatisfactory owing to the quality of the radar and its calibration, and to uncertainties of the radar-raingage intercalibration.

18. There is continuing need for research in establishing seedability criteria; that is, definition of physical cloud conditions when seeding will be effective in increasing precipitation or in bringing about some other desired weather change.

19. Mathematical models used to describe cloud processes or account for interaction of cloud systems and larger scale weather systems greatly oversimplify the real atmosphere; therefore, model research must be coupled with field research.³¹

GOVERNMENTAL ISSUES

The basic problem which encompasses all governmental weather modification issues revolves about the question of the respective roles, if any, of the Federal, State, and local governments. Resolution of this fundamental question puts into perspective the specific issues of where in the several governmental levels, and to what extent, should goals be set, policy established, research and/or operations supported, activities regulated, and disputes settled. Part of this basic question includes the role of the international community, considered in another section on international issues;³² the transnational character of weather modification may one day dictate the principal role to international organizations.

Role of the Federal Government

Because weather modification cannot be restricted by State boundaries and because the Federal Government has responsibilities for resource development and for reduction of losses from natural hazards, few would argue that the Federal Government ought not to have some interest and some purpose in development and possible use of weather modification technology. The following broad and specific issues on the role of the Federal Government in weather modification are among those which may be considered in developing a Federal policy:

1. Should a major policy analysis be conducted in an attempt to relate weather modification to the Nation's broad goals: that is, improving human health and the quality of life, maintaining national security, providing sufficient energy supplies, enhancing environmental quality, and the production of food and fiber? Barbara Farhar suggests that such a study has not been, but ought to be, undertaken.³³

³⁰ Ibid.

³¹ Fleagle et al., "Weather Modification in the Public Interest," 1973, p. 57.

³² See p. 23.

³³ Farhar, Barbara C., "The Societal Implications of Weather Modification: a Review of Issues Toward a National Policy." Background paper prepared for the U.S. Department of Commerce Weather Modification Advisory Board, Mar. 1, 1977, p. 2.

2. Should the Federal Government commit itself to planned weather modification as one of several priority national goals? It can be argued that such commitment is important since Federal program support and political attitudes have an important overall influence on the development and the eventual acceptance and application of this technology.

3. Is there a need to reexamine, define, and facilitate a well-balanced, coordinated, and adequately funded Federal research and development program in weather modification? Many argue that the current Federal research program is fragmented and that the level of funding is subcritical.

4. Is there a suitable Federal role in weather modification activities beyond that of research and development—such as project evaluation and demonstration and operational programs? If such programs are advisable, how can they be identified, justified, and established?

5. Should the practice of providing Federal grants or operational services by Federal agencies to States for weather modification in times of emergency be reexamined, and should procedures for providing such grants and services be formalized? It has been suggested that such assistance in the past has been haphazard and has been provided after it was too late to be of any practical benefit.

6. Should the organizational structure of the Federal Government for weather modification be reexamined and reorganized? If so, what is the optimum agency structure for conducting the Federal research program and other functions deemed to be appropriate for the Federal Government?

7. What is the role of the Federal Government, if any, in regulation of weather modification activities, including licensing, permitting, notification, inspection, and reporting? If such a role is to be modified or expanded, how should existing Federal laws and/or regulations be modified?

8. If all or any of the regulatory functions are deemed to be more appropriate for the States than for the Federal Government, should the Federal Government consider mandating minimum standards and some uniformity among State laws and regulations?

9. Should the Federal Government attempt to develop a means adequate for governing the issues of atmospheric water rights between States, on Federal lands, and between the United States and neighboring countries?

10. Where federally sponsored research or possible operational weather modification projects occupy the same locale as local or State projects, with the possibility of interproject contamination, should a policy on project priorities be examined and established?

11. Should the Federal Government develop a policy with regard to the military use of weather modification and the active pursuit of international agreements for the peaceful uses of weather modification? This has been identified as perhaps one of the most important areas of Federal concern.³⁴

12. Is there a need to examine and define the Federal responsibility for disseminating information about the current state of weather modification technology and about Federal policy, including the capability for providing technical assistance to the States and to others?

³⁴Farhar, Barbara C., "What Does Weather Modification Need"—In preprints of the Sixth Conference on Planned and Inadvertent Weather Modification, Oct. 10-13, 1977, Champaign, Ill., Boston, American Meteorological Society, 1977, p. 299.

13. Should there be a continuing review of weather modification technology capabilities so that Federal policy can be informed regarding the readiness of technologies for export to foreign nations, with provision of technical assistance where and when it seems feasible? ³⁵

14. How does the principle of cooperative federalism apply to weather modification research projects and possible operations carried out within the States? Should planning of projects with field activities in particular States be done in consultation with the States, and should cooperation with the States through joint funding and research efforts be encouraged?

15. What should be the role of the single Federal agency whose activities are most likely to be affected significantly by weather modification technology and whose organization is best able to provide advisory services to the States—the U.S. Department of Agriculture? Among the several agencies involved in weather modification, the Department of Agriculture has demonstrated least official interest and has not provided appreciable support to development of the technology.³⁶

Roles of State and local governments

State and local ³⁷ governments are in many ways closer to the public than the Federal Government—often as a result of more direct contact and personal acquaintance with officials and through greater actual or perceived control by the voters. Consequently, a number of weather modification functions, for both reasons of practical efficiency and social acceptance, may be better reserved for State and/or local implementation. Since weather phenomena and weather modification operations cannot be restricted by State boundaries or by boundaries within States, however, many functions cannot be carried out in isolation. Moreover, because of the economy in conducting research and development on a common basis—and perhaps performing other functions as well—through a single governmental entity, such as an agency or agencies of the Federal Government, it may be neither feasible nor wise for State governments (even less for local jurisdictions) to carry out all activities.

Thus, there are activities which might best be reserved for the States (and possibly for local jurisdictions within States), and those which more properly belong to the Federal Government. In the previous list of issues on the role of the Federal Government, there was allusion to a number of functions which might, wholly or in part, be the responsibility of either Federal or State governments; most of these will not be repeated here. Issues and problems concerned primarily with State and local government functions are listed below:

1. State weather modification laws, where they exist, are nonuniform in their requirements and specifications for licensing, permitting, inspection, reporting, liabilities, and penalties for violations. Moreover, some State laws and policies favor weather modification, while others oppose the technology.

2. Authorities for funding operational and research projects within States and local jurisdictions within States, through public funds

³⁵ Ibid.

³⁶ Changnon, "The Federal Role in Weather Modification," p. 11.

³⁷ "Local" here refers broadly to any jurisdiction below the State level; it could include cities, townships, counties, groups of counties, water districts, or any other organized area operating under public authority.

or through special tax assessments, vary widely and, except in a few States, do not exist.

3. Decisionmaking procedures for public officials appear to be often lacking; these could be established and clarified, especially as the possibility of more widespread application of weather modification technology approaches.

4. Many public officials, usually not trained in scientific and engineering skills, often do not understand weather modification technology, its benefits, and its potential negative consequences. Some training of such officials could contribute to their making wise decisions on the use of the technology, even without complete information on which to base such decisions.

5. Many weather modification decisions have had strong political overtones, with some legislators and other public officials expressing their views or casting their votes allegedly on the basis of political expediency rather than on the basis of present or potential societal benefits.

6. State and local authorities may need to provide for the education of the general public on the rudiments of weather modification, on its economic benefits and disbenefits, and on other societal aspects.

7. To keep communication channels open, mechanisms such as public hearings could be established to receive comments, criticisms, and general public sentiments on weather modification projects from individual citizens and from various interest groups.

8. Criteria and mechanisms have not been established for compensating those individuals or groups within States who might be economically injured from weather modification operations.

9. Questions of water rights within States, as well as between States, have not been addressed and/or resolved in a uniform manner.

LEGAL ISSUES

Legal issues in weather modification are complex and unsettled. They can be discussed in at least four broad categories:

1. Private rights in the clouds;
2. Liability for weather modification;
3. Interstate legal issues; and
4. International legal issues.³⁸

The body of law on weather modification is slight, and existing case law offers few guidelines to determine these issues. It is often necessary, therefore, to analogize weather modification issues to more settled areas of law such as those pertaining to water distribution.

Private rights in the clouds

The following issues regarding private rights in the clouds may be asked:

Are there any private rights in the clouds or in the water which may be acquired from them?

Does a landowner have any particular rights in atmospheric water?

Does a weather modifier have rights in atmospheric water?

³⁸ Questions on regulation or control of weather modification activities through licensing and permitting, while of a basic legal nature, are related to important administrative functions and are dealt with under issues concerned with Federal and State activities.

Some State statutes reserve the ownership or right to use atmospheric water to the State.³⁹

There is no general statutory determination of ownership of atmospheric water and there is no well-developed body of case law. Consequently, analogies to the following general common law doctrines may be helpful, but each has its own disadvantages when applied to weather modification:

1. The doctrine of natural rights, basically a protection of the landowner's right to use his land in its natural condition (i.e., precipitation is essential to use of the land as are air, sunlight, and the soil itself).

2. The ad coelum doctrine which states that whoever owns the land ought also to own all the space above it to an indefinite extent.

3. The doctrine of riparian rights, by which the one owning land which abuts a watercourse may make reasonable use of the water, subject to similar rights of others whose lands abut the watercourse.

4. The doctrine of appropriation, which gives priority of right based on actual use of the water.

5. The two main doctrines of ownership in the case of oil and gas (considered, like water, to be "fugitive and migratory" substances); that is, (a) the non-ownership theory, by which no one owns the oil and gas until it is produced and anyone may capture them if able to do so; and (b) the ownership-in-place theory, by which the landowner has the same interest in oil and gas as in solid minerals contained in his land.

6. The concept of "developed water," that is, water that would not be available or would be lost were it not for man's improvements.

7. The concept of "imported water," that is, water brought from one watershed to another.

Liability for weather modification

Issues of liability for damage may arise when drought, flooding, or other severe weather phenomena occur following attempts to modify the weather. Such issues include causation as well as nuisance, strict liability, trespass, and negligence. Other issues which could arise relate to pollution of the air or water through introduction of artificial nucleants such as silver iodide, into the environment. While statutes of 10 States discuss weather modification liability, there is much variation among the specific provisions of the laws in those States.⁴⁰

Before any case can be made for weather modification liability based upon causation it must be proven that the adverse weather conditions were indeed brought about by the weather modifier, a very heavy burden of proof for the plaintiff. In fact, the scientific uncertainties of weather modification are such that no one has ever been able to establish causation of damage through these activities. As weather modification technology is improved, however, the specter of a host of liability issues is expected to emerge as evidence for causation becomes more plausible.

While the general defense of the weather modifier against liability charges is that causation has not been established, he may also use as further defense the arguments based upon immunity, privilege, consent, and waste.

³⁹ See p. 450, ch. 11, and app. D.

⁴⁰ See discussion p. 453 in ch. 11 and app. D.

Interstate legal issues

When weather modification activities conducted in one State affect another State as well, significant issues may arise. The following problem categories are examples of some generally unresolved interstate issues in weather modification:

1. There may be the claim that cloud seeding in one State has removed from the clouds water which should have fallen in a second State or that excessive flooding in a neighboring State has resulted from seeding in a State upwind.

2. Operation of cloud-seeding equipment near the border in one State may violate local or State ordinances which restrict or prohibit weather modification in an adjacent State, or such operations may conflict with regulations for licensing or permitting of activities within the bordering State.

Some States have attempted to resolve these issues through specific legislation and through informal bilateral agreements.⁴¹ Another approach would be through interstate compact, though such compacts require the consent of Congress. No compacts specifically concerned with weather modification currently exist, though some existing compacts allocating waters in interstate streams may be applicable to weather modification.

International legal issues

Because atmospheric processes operate independent of national borders, weather modification is inherently of international concern. International legal issues have similarities to domestic interstate activities and dangers. The following serious international questions, which have arisen in conjunction with a developing capability to modify the weather, have been identified by Orfield:⁴²

Do countries have the right to take unilateral action in all weather modification activities?

What liability might a country incur for its weather modification operations which [might] destroy life and property in a foreign State?

On what theory could and should that State base its claim?

The primary international legal issue regarding weather modification is that of liability for transnational injury or damage, which could conceivably result from any of the following situations:

(1) injury or damage in another nation caused by weather modification activities executed within the United States;

(2) injury or damage in another nation caused by weather modification activities executed in that nation or a third nation by the United States or a citizen of the United States;

(3) injury or damage in another nation caused by weather modification activities executed in an area not subject to the jurisdiction of any nation (e.g., over the high seas), by the United States or a citizen thereof; and

(4) injury or damage to an alien or an alien's property within the United States caused by weather modification activities executed within the United States.

⁴¹ See discussion p. 457 in ch. 11 and app. D.

⁴² Orfield, Michael B., "Weather Genesis and Weather Neutralization; a New Approach to Weather Modification," *California Western International Law Journal*, vol. 6, no. 2, spring 1976, p. 414.

Whereas domestic weather modification law is confused and unsettled, international law in this area is barely in the formative stage. In time, ramifications of weather modification may lead to major international controversy.⁴³

ECONOMIC ISSUES

The potential for long-term economic gains through weather modification cannot be denied; however, current economic analyses are tenuous in view of present uncertainty of the technology and the complex nature of attendant legal and economic problems. Meaningful economic evaluation of weather modification activities is thus limited to special, localized cases, such as the dispersal of cold fog at airports, where benefit-cost ratios greater than 5 to 1 have been realized through savings in delayed or diverted traffic. Various estimated costs for increased precipitation through cloud seeding range from \$1.50 to \$2.50 per acre-foot in the western United States.

Issues complicating economic analyses of weather modification

Costs of most weather modification operations are usually relatively small and are normally believed to be only a fraction of the benefits obtained through such operations. However, if all the benefits and all the costs are considered, benefit-cost ratios may be diminished. While direct costs and benefits from weather modification are reasonably obvious, indirect costs and benefits are elusive and require further study of sociological, legal, and ecological implications.

In analyzing benefit-cost ratios, some of the following considerations need to be examined:

Weather modification benefits must be considered in terms of the costs for achieving the same objectives as increased precipitation, e.g., through importation of water, modified use of agricultural chemicals, or introduction of improved plant strains.

Costs for weather modification operations are so low in comparison with other agricultural investments that farmers may gamble in spending the 5 to 20 cents per acre for operations designed to increase rainfall or suppress hail in order to increase yield per acre, even though the results of the weather modification operations may be doubtful.

Atmospheric conditions associated with prolonged droughts are not conducive to success in increasing precipitation; however, under these conditions, it is likely that increased expenditures may be made for operations which offer little hope of economic return.

Increased precipitation, obtained through a weather modification program sponsored and funded by a group of farmers, can also benefit other farmers who have not shared in the costs; thus, the benefit-cost ratio to those participating in the program is higher than it need be if all share in its costs.

As weather modification technology develops and programs become more sophisticated, increased costs for equipment and labor will increase direct costs to clients; indirect costs resulting from increased State license and permit fees and liability insurance for operators will probably also be passed on to the customer.

⁴³ See ch. 10 on international aspects and p. 468, ch. 11, on international legal aspects of weather modification.

The sophistication of future programs will likely incur additional costs for design, evaluation, and program information activities, along with supporting meteorological prediction services; these costs will be paid from public funds or by private clients, in either case reducing the overall benefit-cost ratios.

Ultimate costs for compensation to those incurring disbenefits from weather modification operations will offset overall benefits and thus reduce benefit-cost ratios.

Weather modification and conflicting interests

There are numerous cases of both real and perceived economic losses which one or more sectors of the public may suffer while another group is seeking economic advantage through some form of weather modification. Overall benefits from weather modification are accordingly reduced when net gains are computed from such instances of mixed economic advantages and disadvantages. Benefits to the parties seeking economic gain through weather modification will be directly reduced at such time when mechanisms are established for compensating those who have suffered losses. The following are some examples of such conflicting situations:

Successful suppression of hail may be valuable in reducing crop damage for orchardists while other agricultural crops may suffer from decrease of rain concomitant with the hail decrease.

Additional rainy days may be of considerable value to farmers during their growing season but may be detrimental to the financial success of outdoor recreational enterprises.

Increased snowpack from orographic cloud seeding may be beneficial to agricultural and hydroelectric power interests but increases the costs for maintaining free passage over highways and railroads in mountainous areas.

Successful abatement of winds from severe storms, such as those of hurricanes, may result in decreased precipitation necessary for agriculture in nearby coastal regions or may redistribute the adverse storm effects, so that one coastal area is benefitted at the expense of others.

SOCIAL ISSUES

It has been said that "weather modification is a means toward socially desired ends, not an end in itself. It is one potential tool in a set of possible societal adjustments to the vagaries of the weather. Identifying when, where, and how to use this tool, once it is scientifically established, is the primary need in weather modification."⁴⁴ It is likely that, in the final analysis, the ultimate decisions on whether weather modification should and will be used in any given instance or will be adopted more generally as national or State programs depends on social acceptance of this tool, no matter how well the tool itself has been perfected. That this is increasingly the case has been suggested by numerous examples in recent years. Recently Silverman said:

Weather modification, whether it be research or operations, will not progress wisely, or perhaps at all, unless it is considered in a context that includes everyone

⁴⁴ Farhar, Barbara C. "What Does Weather Modification Need?" In preprints of the Sixth Conference on Planned and Inadvertent Weather Modification, October 10-13, 1977, Champaign, Ill. Boston, American Meteorological Society, 1977. p. 296.

that may be affected. We must develop and provide a new image of weather modification.⁴⁵

Regardless of net economic benefits, a program is hard to justify when it produces obvious social losses as well as gains.

Research in the social science of weather modification has not kept pace with the development of the technology, slow as that has been. In time, this failure may be a serious constraint on further development and on its ultimate application. In the past, organized opposition has been very effective in retarding research experiments and in curtailing operational cloud-seeding programs. Thus, there is need for an expanded effort in understanding public behavior toward weather modification and for developing educational programs and effective decisionmaking processes to insure intelligent public involvement in eventual application of the technology.

Social issues discussed in this section are those which relate to public behavior and public response to weather modification, while societal issues are generally considered to include economic, legal, and other nontechnical issues as well as the social ones. These other aspects of societal issues were discussed in preceding sections. In the subsections to follow there are summaries of social implications of weather modification, the need for public education, and the problem of decisionmaking.

Social factors

It has been said that social factors are perhaps the most elusive and difficult weather modification externalities to evaluate since such factors impinge on the vast and complex area of human values and attitudes.⁴⁶ Fleagle, et al., identified the following important social implications of weather modification, which would presumably be taken into account in formulation of policies:⁴⁷

1. The individuals and groups to be affected, positively or negatively, by the project must be defined. An operation beneficial to one party may actually harm another. Or an aggrieved party may hold the operation responsible * * * for damage * * * which might occur at the same time or following the modification.
2. The impact of a contemplated weather modification effort on the general well-being of society and the environment as a whole must be evaluated. Consideration should be given to conservationists, outdoor societies, and other citizens and groups representing various interests who presently tend to question any policies aimed at changes in the physical environment. It is reasonable and prudent to assume that, as weather modification operations expand, questioning and opposition by the public will become more vocal.
3. Consideration must be given to the general mode of human behavior in response to innovation. There are cases where local residents, perceiving a cause and effect relationship between economic losses from severe weather and nearby weather modification operations, have continued to protest, and even to threaten violence, after all operations have been suspended.
4. The uniqueness and complexity of certain weather modification operations must be acknowledged, and special attention should be given to their social and legal implications. The cases of hurricanes and tornadoes are especially pertinent. Alteration of a few degrees in the path of a hurricane may result in its missing a certain area * * * and ravaging * * * instead, a different one. The decision on whether such an operation is justified can reasonably be made only at the highest level, and would need to be based on the substantial scientific finding that the anticipated damages would be less than those originally predicted had the hurricane been allowed to follow its course.

⁴⁵ Silverman, Bernard A. "What Do We Need in Weather Modification?" In preprints of the Sixth Conference on Planned and Inadvertent Weather Modification, October 10-13, 1977, Champaign, Ill. Boston, American Meteorological Society, 1977. p. 310.

⁴⁶ Fleagle, Crutchfield, Johnson, and Abdo. "Weather Modification in the Public Interest." 1974. p. 37-38.

⁴⁷ Ibid., p. 38-40.

5. Attention must be given to alternatives in considering a given weather modification proposal. The public may prefer some other solution to an attempt at weather tampering which may be regarded as predictable and risky. Furthermore, alternative policies may tend to be comfortable extensions of existing policies, or improvements on them, thus avoiding the public suspicion of innovation. In an area such as weather modification, where so many uncertainties exist, and where the determination or assigning of liability and responsibility are far from having been perfected, public opposition will surely be aroused. Any alternative plan or combination of plans will have its own social effects, however, and it is the overall impact of an alternative plan and the adverse effects of not carrying out such a plan which, in the final analysis, should guide decisions on alternative action.

6. Finally, it is important to recognize that the benefits from a weather modification program may depend upon the ability and readiness of individuals to change their modes of activity. The history of agricultural extension work in the United States suggests that this can be done successfully, but only with some time lag, and at a substantial cost. Social research studies suggest that public perception of flood, earthquake, and storm hazards is astonishingly casual.

Need for public education on weather modification

The previous listing of social implications of weather modification was significantly replete with issues derived from basic human attitudes. To a large extent these attitudes have their origin in lack of information, misconceptions, and even concerted efforts to misinform by organized groups which are antagonistic to weather modification. As capabilities to modify weather expand and applications are more widespread, it would seem probable that this information gap would also widen if there are no explicit attempts to remedy the situation. "At the very least," according to Fleagle, et al., "a large-scale continuing program of education (and perhaps some compulsion) will be required if the potential social gains from weather modification are to be realized in fact."⁴⁸ Whether such educational programs are mounted by the States or by some agency of the Federal Government is an issue of jurisdiction and would likely depend on whether the Federal Government or the States has eventual responsibility for management of operational weather modification programs. Information might also be provided privately by consumer groups, professional organizations, the weather modification industry, or the media.

It is likely that educational programs would be most effective if a variety of practical approaches are employed, including use of the news media, publication of pamphlets at a semitechnical level, seminars and hearings, and even formal classes. Probably the latter categories would be most appropriate for civic groups, Government officials, businessmen, or other interests who are likely to be directly affected by contemplated operations.

The following list of situations are examples of public lack of understanding which could, at least in part, be remedied through proper educational approaches:

There is much apprehension over claims of potential danger of a long-lasting nature on climate, which could supposedly result from both inadvertent and planned modification of the weather, with little insight to distinguish between the causes and the scales of the effects.

There have been extravagant claims, propagated through ignorance or by deliberate distortion by antagonistic groups, about

⁴⁸ Ibid., p. 40.

the damaging effects of cloud seeding on ecological systems, human health, and air and water quality.

The controversies between opposing groups of scientists on the efficacy of weather modification technologies and between scientists and commercial operators on the readiness of these technologies for application has engendered a mood of skepticism and even mistrust of weather modification on the part of a public which is largely uninformed on technical matters.

The public has often been misinformed by popular news media, whose reporters seek to exploit the spectacular in popular weather modification "stories" and who, themselves usually uninformed in technical aspects of the subject, tend to oversimplify and distort the facts associated with a rather complex science and technology.

There has been an organized effort on the part of groups opposed to weather modification to mount an educational program which runs counter to the objectives of informing the public about the potential benefits of a socially acceptable technology of weather modification.

Portions of the public have acquired a negative impression that meteorologists and Government officials concerned with weather modification are irresponsible as a result of past use, or perceived present and future use, of the technology as a weapon of war.

Lack of information to the public has sometimes resulted in citizen anger when it is discovered that a seeding project has been going on in their area for some time without their having been informed of it.

Decisionmaking

"The nature of weather processes and the current knowledge about them require that most human decisions as to weather modification must be made in the face of uncertainty. This imposes special restraints on public agencies and it increases the difficulty of predicting how individual farmers, manufacturers, and others who are directly affected by weather would respond to changes in weather characteristics."⁴⁹ The situation since 1965 when this statement was made has changed little with regard to predictability of weather processes and their modification. There has also been little progress toward developing decisionmaking processes which can be applied, should the need arise, on whether or not weather modification should be employed.

A number of studies on social attitudes indicate that the preference of most citizens is that decisionmaking in such areas as use or restraint from use of weather modification should be at the local level, owing to the feeling that citizens' rights and property are best protected when decisions are made by officials over whom they have the most direct control. Farhar says that evidence suggests that one important condition for public acceptance of weather modification technology is public involvement in the decision process, especially in civic decisions.⁵⁰ Procedures must then be developed for enabling local

⁴⁹ Special Commission on Weather Modification. "Weather and Climate Modification." NSF 66-3, 1965, p. 96.

⁵⁰ Farhar, Barbara C. "The Public Decides About Weather Modification." *Environment and Behavior*, vol. 9, No. 3, September 1977, p. 307.

officials, probably not technically trained, to make such decisions intelligently. Such decisions must be based both on information received from Federal or State technical advisers and on the opinions of local citizens and interest groups.

INTERNATIONAL ISSUES

International agreements regarding weather modification experiments and operations have been very limited. There exists a United States-Canada agreement, which requires consultation and notification of the other country when there is the possibility that weather-modification activities of one country could affect areas across the border.⁵¹ Earlier understandings were reached between the United States and Canada concerning experiments over the Great Lakes and with the United Kingdom in connection with hurricane modification research in the Atlantic.⁵² Recent attempts to reach agreement with the Governments of Japan and the People's Republic of China for U.S. experiments in the Far East on modification of typhoons were unsuccessful, though such research was encouraged by the Philippines. There is current intention to reach an agreement with Mexico on hurricane research in the eastern Pacific off that nation's coast.

During 1976, 25 nations reported to the World Meteorological Organization that they had conducted weather modification activities.⁵³ There have been two principal international activities, dealing with somewhat different aspects of weather modification, in recent years. One of these is the preparation and design of a cooperative experiment under the auspices of the World Meteorological Organization, called the Precipitation Enhancement Experiment (PEP); while the other is the development of a convention by the United Nations on the prohibition of hostile use of environmental modification.⁵⁴

The following international considerations on research and operational weather modification activities can be identified:

1. There is a common perception of a need to insure that the current high level of cooperation which exists in the international community with regard to more general meteorological research and weather reporting will be extended to development and peaceful uses of planned weather modification.

2. There is now no body of international law which can be applied to the potentially serious international questions of weather modification, such as liability or ownership of atmospheric water resources.⁵⁵

3. Past use by the United States, and speculated current or future use by various countries, of weather modification as a weapon have raised suspicions as to the possible intent in developing advertent weather modification technology.

4. There have been charges that weather modification research activities were used to divert severe weather conditions away from the

⁵¹ The United States-Canada agreement on weather modification is reproduced in app. F.

⁵² Taubenfeld, Howard J., "National Weather Modification Policy Act of 1976; International Agreements." Background paper for use of the U.S. Department of Commerce Weather Modification Advisory Board, March 1977, p. 13.

⁵³ See table 1, ch. 9, p. 409.

⁵⁴ These activities and other international aspects of weather modification are discussed in ch. 10.

⁵⁵ See previous section on legal issues, p. 17.

United States at the expense of other countries or that such activities have resulted in damage to the environment in those countries.⁵⁶

5. As in domestic research projects, there are allegations of insufficient funding over periods of time too short to achieve significant results in the case of internationally sponsored experiments; in particular, many scientists feel that a means should be devised to insure that the planned Precipitation Enhancement Project (PEP) receives adequate continuous support.

6. Other nations should be consulted with regard to any planned weather modification activities by the United States which might conceivably affect, or be perceived to affect, those countries.

ECOLOGICAL ISSUES

The body of research on ecological effects of weather modification is limited but significantly greater than it was a decade ago. It is still true that much remains unknown about ecological effects of changes to weather and climate.

Economically significant weather modification will always have an eventual ecological effect, although appearance of that effect may be hidden or delayed by system resilience and/or confused by system complexity. It may never be possible to predict well the ecological effects of weather modification; however, the more precisely the weather modifier can specify the effects his activities will produce in terms of average percentage change in precipitation (or other variables), expected seasonal distribution of the induced change, expected year-to-year distribution of the change, and changes in relative form of precipitation, the more precise can be the ecologist's prediction of possible ecological effects.

Ecological effects will result from moderate weather-related shifts in rates of reproduction, growth, and mortality of plants and animals; they will rarely be sudden or catastrophic. Accordingly, weather modifications which occur with regularly over time are the ones to which biological communities will react. Adjustments of plant and animal communities will usually occur more slowly in regions of highly variable weather than in those with more uniform conditions. Deliberate weather modification is likely to have greater ecological impact in semiarid systems and less impact in humid ones. Since precipitation augmentation, for example, would have the greatest potential for economic value and is, therefore, likely to have its greatest potential application in such areas, the ecological impacts in transition areas will be of particular concern.

Although widespread cloud seeding could result in local, temporary increases in concentrations of silver (from the most commonly used seeding agent, silver iodide), approaching the natural quantities in surface waters, the exchange rates would probably be an order of magnitude lower than the natural rates. Even in localized areas of precipitation management, it appears that exchange rates will be many orders of magnitude smaller than those adversely affecting plants and soils. Further research is required, however, especially as other potential seeding agents are introduced.

⁵⁶ For example, there were charges that attempts to mitigate severe effects of Hurricane Fifi in 1975 caused devastation to Honduras, a charge which the United States officially denied, since no hurricanes had been seeded under Project Stormfury since 1971.

CHAPTER 2

HISTORY OF WEATHER MODIFICATION

(By Robert E. Morrison, Specialist in Earth Sciences, Science Policy Research Division, Congressional Research Service)

INTRODUCTION

The history of the desire to control the weather can be traced to antiquity. Throughout the ages man has sought to alleviate droughts or to allay other severe weather conditions which have adversely affected him by means of magic, supplication, pseudoscientific procedures such as creating noises, and the more on less scientifically based techniques of recent times.

The expansion in research and operational weather modification projects has increased dramatically since World War II; nevertheless, activities predating this period are of interest and have also provided the roots for many of the developments of the "modern" period. In a 1966 report for the Congress on weather modification, Lawton Hartman stated three reasons why a review of the history of the subject can be valuable: (1) Weather modification is considerably older than is commonly recognized, and failure to consider this fact can lead to a distorted view of current problems and progress. (2) Weather modification has not developed as an isolated and independent field of research, but for over a century has been parallel to and related to progress in understanding weather processes generally. (3) Earlier experiences in weather modification may not have been very different from contemporary experiences in such matters as experimental design, evaluation of results, partially successful projects, and efforts to base experiments on established scientific principles.¹

Hartman found that the history of weather modification can be conveniently divided into five partially overlapping periods.² He refers to these as (1) a prescientific period (prior to about 1839); (2) an early scientific period (extending approximately from 1839 through 1891); (3) a period during which elements of the scientific framework were established (from about 1875 to 1933); (4) the period of the early cloud-seeding experiments (1921 to 1946); and (5) the modern period, beginning with the work of Langmuir, Schaefer, and Vonnegut (since 1946). This same organization is adopted in discussions below; however, the four earlier periods are collected into one section, while the more significant history of the extensive activities of the post-1946 period are treated separately.

¹ Hartman, Lawton M., "History of Weather Modification." In U.S. Congress, Senate Committee on Commerce. "Weather Modification and Control." Washington, D.C.: U.S. Government Printing Office, 1966 (89th Cong., 2d sess., Senate Rept. No. 1139; prepared by the Legislative Reference Service, the Library of Congress, at the request of Warren G. Magnuson), p. 11.

² Ibid.

HISTORY OF WEATHER MODIFICATION PRIOR TO 1946

PRESCIENTIFIC PERIOD

From ancient times through the early 19th century, and even since, there have been reported observations which led many to believe that rainfall could be induced from such phenomena as great noises and extensive fires. Plutarch is reported to have stated, "It is a matter of current observation that extraordinary rains pretty generally fall after great battles."³ Following the invention of gunpowder, the frequency of such claims and the conviction of those espousing this hypothesis increased greatly. Many cases were cited where rain fell shortly after large battles. A practical use of this phenomenon was reported to have occurred in the memoirs of Benvenuto Cellini when, in 1539 on the occasion of a procession in Rome, he averted an impending rainstorm by firing artillery in the direction of the clouds, "which had already begun to drop their moisture."⁴

William Humphreys posed a plausible explanation for the apparently high correlation between such weather events and preceding battles. He noted that plans were usually made and battles fought in good weather, so that after the battle in the temperate regions of Europe or North America, rain will often occur in accordance with the natural 3- to 5-day periodicity for such events.⁵ Even in modern times there was the conviction that local and global weather had been adversely affected after the explosion of the first nuclear weapons and the various subsequent tests in the Pacific and elsewhere.⁶ Despite statements of the U.S. Weather Bureau and others pointing out the fallacious reasoning, such notions became widespread and persistent.⁷

In addition to these somewhat rational though unscientific observations, many of which were accompanied by testimony of reliable witnesses, there had been, and there still exist in some primitive cultures, superstitions and magical practices that accompany weather phenomena and attempts to induce changes to the weather. Daniel Halacy relates a number of such superstitiouslike procedures which have been invoked in attempts to bring rain to crops during a drought or to change the weather in some other way so as to be of particular benefit to man:⁸

Primitive rainmakers would often use various intuitive gestures, such as sprinkling water on the soil that they wanted the heavens to douse, blowing mouthfuls of water into the air like rain or mist, hammering on drums to imitate thunder, or throwing firebrands into the air to simulate lightning.

Women would carry water at night to the field and pour it out to coax the skies to do likewise.

American Indians blew water from special pipes in imitation of the rainfall.

It was believed that frogs came down in the rain because many were seen following rain; therefore, frogs were hung from trees so that the heavens would pour down rain upon them.

Sometimes children were buried up to their necks in the parched ground and then cried for rain, their tears providing the imitative magic.

³ Ward, R. De C., "Artificial Rain: a Review of the Subject to the Close of 1889." *American Meteorological Journal*, vol. 8, May 1891-April 1892, p. 484.

⁴ *Ibid.*, p. 493.

⁵ Humphreys, William J., "Rain Making and Other Weather Vagaries." Baltimore, The Williams and Wilkins Co., 1926, p. 31.

⁶ Byers, Horace R., "History of Weather Modification." In Wilnot N. Hess (editor), "Weather and Climate Modification," New York, Wiley, 1974, p. 4.

⁷ *Ibid.*

⁸ Halacy, Daniel S., Jr., "The Weather Changers," New York, Harper & Row, 1968, pp. 52-63.

In China, huge paper dragons were part of religious festivals to bring rain; if drought persisted, the dragon was angrily torn to bits.

North American Indians roasted young women from enemy tribes over a slow fire, then killed them with arrows before eating their hearts and burying their remains in the fields they wanted irrigated with rainfall.

Scottish witches conjured up the wind by beating a stone three times with a rag dipped in water, among intonations like those of characters in a Shakespearean play.

New Guinea natives used wind stones upon which they tapped with a stick, the force of the blow bringing anything from a zephyr to a hurricane.

Pregnant women in Greenland were thought to be able to go outdoors, take a breath, and exhale it indoors to calm a storm.

In Scandinavian countries witches sold knotted bits of string and cloth which, supposedly, contained the wind; untying one knot at sea would produce a moderate wind, two a gale, and three a violent storm.

Australian bushmen thought that they could delay the Sun by putting a clod of dirt in the fork of a tree at just the height of the Sun, or hasten its departure by blowing sand after it.

Bells have been thought to prevent hail, lightning, and windstorms, and sometimes they are still rung today for this purpose.

EARLY SCIENTIFIC PERIOD

James P. Espy was a 19th century American meteorologist known especially for his development of a theory of storms based on convection. Recognizing that a necessary condition for rainfall is the formation of clouds by condensation of water vapor from rising air, Espy considered that rain could well be induced artificially when air is forced to rise as a result of great fires, reviving a belief of the pre-scientific era but using scientific rationale. In the *National Gazette* in Philadelphia of April 5, 1839, he said:

From principles here established by experiment, and afterward confirmed by observation, it follows, that if a large body of air is made to ascend in a column, a large cloud will be generated and that that cloud will contain in itself a self-sustaining power, which may move from the place over which it was formed, and cause the air over which it passes, to rise up into it, and thus form more cloud and rain, until the rain may become more general.⁹

If these principles are just, when the air is in a favorable state, the bursting out of a volcano ought to produce rain; and such is known to be the fact; and I have abundant documents in my possession to prove it.

So, under very favorable conditions, the bursting out of great fires ought to produce rain; and I have many facts in my possession rendering it highly probable, if not certain, that great rains have sometimes been produced by great fires.¹⁰

Later in the same article Espy stated that:

From these remarkable facts above, I think it will be acknowledged that there is some connection between great fires and rains other than mere coincidence. But now, when it is demonstrated by the most decisive evidence, the evidence of experiment, that air, in ascending into the atmosphere in a column, as it must do over a great fire, will cool by diminished pressure, so much that it will begin to condense its vapor into cloud.¹¹

Espy postulated three mechanisms which could prevent great fires from providing rain at all times when they occur: (1) If there is a current of air at some height, it sweeps away the uprushing current of air; (2) the dewpoint may be too low to produce rain at all; and (3) there may be an upper stratum of air so light that the rising

⁹ Espy, James P., "Artificial Rains," *National Gazette*, Philadelphia, Apr. 5, 1839. Reprinted in James P. Espy, "Philosophy of Storms," Boston, Little & Brown, 1841, pp. 493-494.

¹⁰ *Ibid.*, p. 494.

¹¹ *Ibid.*, p. 496.

column may not be able to rise far enough into it to cause rain.¹² He proposed an experiment in which he would set fire to a "large mass of combustibles," which would be ready for the right circumstances and at a time of drought. He added: "Soon after the fire commences, I will expect to see clouds begin to form * * *. I will expect to see this cloud rapidly increase in size, if its top is not swept off by a current of air at a considerable distance above the Earth, until it becomes so lofty as to rain."¹³

For over a decade Espy served as an adviser to the Congress on meteorological problems. He proposed in 1850 what is perhaps the first Federal project for large-scale weather modification. His plan included amassing large quantities of timber in the Western States along a 600- to 700-mile north-south line, to be set on fire simultaneously at regular 7-day intervals. He believed that this fire could have started a "rain of great length" traveling toward the East, not breaking up until reaching "far over the Atlantic Ocean; that it will rain over the whole country east of the place of beginning." The cost of this experiment would "not amount to half a cent a year to each individual in the United States."¹⁴ Congress did not endorse the proposal for reasons which are unknown; however, Fleagle speculates that perhaps this failure was due to the fact that Congress had not yet accustomed itself to appropriating funds for scientific enterprises.¹⁵

There was continuing controversy over whether or not fire could cause increased rainfall. In an article which appeared in *Nature* in 1871, J. K. Laughton stated that, "The idea that large fires do, in some way, bring on rain, is very old; but it was, I believe, for the first time stated as a fact and explained on scientific grounds by the late Professor Espy."¹⁶ Laughton cited instances where burning brush in hot, dry weather did not result in any rainfall, and he concluded that:

Large fires, explosions, battles, and earthquakes do tend to cause atmospheric disturbance, and especially to induce a fall of rain; but that for the tendency to produce effect, it is necessary that other conditions should be suitable. With regard to storms said to have been caused by some of these agencies, the evidence is still more unsatisfactory; and, in our present ignorance of the cause of storms generally, is quite insufficient to compel us to attribute any one particular gale, extending probably over a wide area, to some very limited and comparatively insignificant disturbance.¹⁷

The 1871 Chicago fire also aroused interest, many believing that the fire was stopped by the rainfall which it had initiated. Ward cites a telegram of the time sent to London which read:

This fire was chiefly checked on the third or fourth day by the heavy and continuous downpour of rain, which it is conjectured is partly due to the great atmospheric disturbances which such an extensive fire would cause, especially when we are told that the season just previous to the outbreak of the fire had been particularly dry.¹⁸

¹² *Ibid.*

¹³ *Ibid.*, p. 499.

¹⁴ Espy, James P. "Second Report on Meteorology to the Secretary of the Navy." U.S. Senate, Executive Documents, No. 39, vol. 11, 31st Cong., 1st sess. Washington, Wm. M. Belt, 1850, p. 20.

¹⁵ Fleagle, Robert G. "Background and Present Status of Weather Modification." In Robert G. Fleagle (editor), "Weather Modification: Science and Public Policy." University of Washington Press, Seattle, 1968, p. 7.

¹⁶ Laughton, J. K., "Can Weather Be Influenced by Artificial Means?" *Nature*, Feb. 16, 1871, p. 306.

¹⁷ *Ibid.*, p. 307.

¹⁸ Reported in Ward, "Artificial Rain; a Review of the Subject to the Close of 1889," 1892, pp. 489-490.

On the other hand, Prof. I. A. Lapham, speaking of the Chicago fire, contradicted the previous account, saying:

During all this time—24 hours of conflagration—no rain was seen to fall, nor did any rain fall until 4 o'clock the next morning; and this was not a very considerable downpour, but only a gentle rain, that extended over a large district of country, differing in no respect from the usual rains. It was not until 4 days afterward that anything like a heavy rain occurred. It is, therefore, quite certain that this case cannot be referred to as an example of the production of rain by a great fire.¹⁹

Lapham goes on to say that, "The case neither confirms nor disproves the Espian theory, and we may still believe the well-authenticated cases where, under favorable circumstances of very moist air and absence of wind, rain has been produced by very large fires."²⁰

Prof. John Trowbridge of Harvard reported in 1872 on his experiments in which he investigated the influence of flares on atmospheric electricity. Noting that the normal atmospheric state is positive and that clearing weather is often preceded by a change from negative to positive charge, he suggested that perhaps large fires may influence the production of rain by changing the electrical state of the atmosphere, since, in his tests, his flame tended "to reduce the positive charge of electricity which generally characterizes the air of fine weather."²¹ He concluded by saying: "The state of our knowledge, however, in regard to the part that electricity plays in atmospheric changes is very meager. The question of the truth of the popular belief that great fires are followed by rain still remains unanswered."²²

Meanwhile, H. C. Russel, president of the Royal Society of South Wales and government astronomer, attempted to dispel the ideas that both cannonading and great fires could be used to produce rain. He hypothesized that, if fire were to have such an effect, rain should arrive within 48 hours following the fire. Reviewing the records of 42 large fires (including two explosions) covering a 21-year period, Russel concluded that there was not one instance in which rain followed within 48 hours as an evident consequence of the fire. He further calculated that to get increased rainfall of 60 percent over a land surface of 52,000 square feet at Sidney would require 9 million tons of coal per day, in an effort to show what magnitude of energy expenditure was necessary and how futile such an attempt would be.²³

Toward the latter part of the 19th century there were a number of ideas and devices invented for producing rain artificially. In 1880 David Ruggles of Virginia patented what he said was "a new and useful mode of producing rain or precipitating rainfalls from rainclouds, for the purpose of sustaining vegetation and for sanitary purposes." His plan included a scheme by which balloons carrying explosives were sent up into the air, the explosives to be detonated in the upper air "by electric currents."²⁴

¹⁹ Lapham, I. A., "The Great Fires of 1871 in the Northwest." *The Journal of the Franklin Institute*, vol. 64, No. 1, July 1872, pp. 46-47.

²⁰ *Ibid.*, p. 47.

²¹ Trowbridge, John, "Great Fires and Rain-storms." *The Popular Science Monthly*, vol. 2, December 1872, p. 211.

²² *Ibid.*

²³ Report of an address by H. C. Russel was given in *Science*, vol. 3, No. 55, Feb. 22, 1884, pp. 229-230.

²⁴ "New Method of Precipitating Rain Falls," *Scientific American*, vol. 43, Aug. 14, 1880, p. 106.

G. H. Bell suggested a rainmaking device, consisting of a hollow tower 1,500 feet high, through which air was to be blown into the atmosphere, the volume of the up-rushing air to be increased through use of a system of tubes around the tower. The inventor considered that the same system could be used to prevent rain, by reversing the blower so that the descending air might "annihilate" the clouds.²⁵

Still other schemes and contrivances were proposed and patented. J. B. Atwater was granted a patent in 1887 for a scheme to dissipate tornadoes by detonating an explosive charge in their centers, and another was granted to Louis Gathman in 1891 for seeding clouds for rain by exploding a shell containing "liquid carbonic acid gas" at cloud height,²⁶ the latter concept antedating by over 50 years the more recent carbon dioxide seeding projects.

There continued to be adherents to the idea that explosions could cause rainfall. This belief was reinforced by "evidence" of such a connection in a book by Edward Powers, called "War and the Weather," published in 1871 and 1890 editions, in which the author recounted the instances in which rain followed battles, mostly from North America and Europe during the 19th century.²⁷

Powers was convinced that:

The idea that rain can be produced by human agency, though sufficiently startling, is not one which, in this age of progress, ought to be considered as impossible of practical realization. Aside from its connection with the superstitions of certain savage tribes, it is an opinion of comparatively recent origin, and is one which cannot be regarded as belonging, in any degree, to a certain class of notions which prevail among the unthinking; * * * on the contrary, it is one which is confined principally to those who are accustomed to draw conclusions only from adequate premises, and * * * founded on facts which have come under their own observation.²⁸

In tones somewhat reminding us of those urging a greater Federal research effort in recent years, Powers proposed that experiments be undertaken for economic benefit:

Judging from the letters which I have received since commencing in 1870 an attempt to bring forward the subject of rains produced by cannon firing, I believe that the country would regard with interest some experiments in the matter, and would not begrudge the expense, even if they should prove unsuccessful in leading to a practical use of the principle under discussion. In some matters connected with science, the Government has justly considered that an expenditure of public funds was calculated to be of public benefit; but where, in anything of the kind it has ever undertaken, has there been so promising a field for such actions as here?²⁹

Powers, upon examining the records of many battles, said:

Let us proceed to facts—facts not one of which, perhaps, would be of any significance if it stood alone and unsupported by the others; but which, taken in the aggregate, furnish the strongest evidence that heavy artillery firing has an influence on the weather and tends to bring rain.³⁰

Perhaps influenced by the arguments of Powers and others, in 1890 the U.S. Congress had become so much interested in and gained

²⁵ "Another Rain Controller," *Scientific American*, vol. 43, Aug. 21, 1880, p. 113.

²⁶ Harrington, Mark W., "Weather-making, Ancient and Modern," *Smithsonian Institution Annual Report*, to July 1894, pp. 249-270.

²⁷ Powers, Edward, "War and the Weather," Delavan, Wis., E. Powers, 1890, revised edition, 202 pp. (An earlier edition was published in Chicago in 1871. Incidentally, the plates for the first edition were destroyed in the Chicago fire, and Powers did not have an opportunity to complete his revision until 1890.)

²⁸ *Ibid.*, p. 5.

²⁹ *Ibid.*, p. 143.

³⁰ *Ibid.*, p. 11.

such faith in the possibility of weather modification that funds were appropriated to support experiments to be carried out under the auspices of the Forestry Division of the U.S. Department of Agriculture. The initial \$2,000 appropriated was increased first to \$7,000, and finally to \$10,000, in the first federally sponsored weather modification project. Of the total appropriated, \$9,000 was to be spent on field experiments. Gen. Robert St. George Dyrenforth was selected by the Department of Agriculture to direct these tests, having earlier conducted tests near Utica, N.Y., and Washington, D.C., using balloons and rockets carrying explosives. The principal experiments were executed near Midland, Tex., using a variety of explosive devices, detonated singly and in volleys, both on the ground and in the air.³¹

According to an interesting account by Samuel Hopkins Adams, Dyrenforth arrived in Texas on a hot day in August 1891 with a company of 80 workers, including " * * * chemists, weather observers, balloon operators, electricians, kitefliers, gunners, minelayers, sappers, engineers, and laborers * * * together with some disinterested scientists, who were to serve as reporters." ³² Adams discusses the apparatus which Dyrenforth took with him:

The expedition's equipment was impressive. There were 68 balloons of from 10 to 12 feet in diameter, and one of 20 feet—all to be filled with an explosive mixture of hydrogen and oxygen. There were also sixty 6-inch mortars, made of pipe, and several tons of rackarock (a terrifying blend of potassium chlorate and nitrobenzol that was the general's favorite "explosive"), dynamite, and blasting powder. Finally, there were the makings of a hundred kites, to be assembled on the scene, and sent up with sticks of dynamite lashed to them. The congressional \$9,000 fell considerably short of sufficing for so elaborate an outfit, but expectant Texans chipped in with liberal contributions and the railroads helped out by supplying free transportation.³³

Dyrenforth carried out five series of trials during 1891 and 1892; one period of sustained cannonading coincided with a heavy down-pour, and the apparent connection provided support to the credibility of many people, who accepted the hypotheses as confirmed. Dyrenforth gave optimistic and promising reports of his results; however, meteorologists and other scientists were critical of his work. It does not appear that the Forestry Division was fervently advocating the research program for which it had responsibility. In 1891, Bernhard E. Fernow, Chief of the Division of Forestry, reported to the Secretary of Agriculture his sentiments regarding the experiments which were to be conducted in the coming summer, with a caution reminiscent of the concerns of many meteorologists of the 1970's:

The theories in regard to the causes of storms, and especially their local and temporal distribution, are still incomplete and unsatisfactory. It can by no means be claimed that we know all the causes, much less their precise action in precipitation. It would, therefore, be presumptuous to deny any possible effects of explosions; but so far as we now understand the forces and methods in precipitating rain, there seems to be no reasonable ground for the expectation that they will be effective. We may say, then, that at this stage of meteorological knowledge we are not justified in expecting any results from trials as proposed for the production of artificial rainfall, and that it were better to increase this knowledge first

³¹ Fleagle, "Background and Present Status of Weather Modification," 1968, pp. 7-8.

³² Adams, Samuel Hopkins, *The New Yorker*, Oct. 9, 1952, pp. 93-100.

³³ *Ibid.*, p. 94.

by simple laboratory investigations and experiments preliminary to experiment on a larger scale.³⁴

In 1893, the Secretary of Agriculture asked for no more public funds for support of this project.³⁵

Fleagle tells about the use of 36 "hail cannons" by Albert Stiger, a town burgomaster, on the hills surrounding his district in Austria in 1896:

The hail cannon consisted of a vertically pointing three-centimeter mortar above which was suspended the smokestack of a steam locomotive. This device not only produced an appalling sound, but also created a smoke ring a meter or more in diameter which ascended at about one hundred feet per second and produced a singing note lasting about ten seconds. Initial successes were impressive, and the hail cannon was widely and rapidly copied throughout central Europe. Accidental injuries and deaths were numerous, and in 1902 an international conference was called by the Austrian government to assess the effects of the hail cannon. The conference proposed two tests, one in Austria and one in Italy, the results of which thoroughly discredited the device.³⁶

Though unsuccessful, the work of Dyrenforth and others had inspired belief in the possibilities of drought alleviation such that a number of unscrupulous "rainmakers" were able to capitalize on the situation. Halacy gives an account of a famous rainmaker of the early 20th century, Charles Warren Hatfield, who operated for about 10 years in the western United States. With a 25-foot platform and a secret device for dispensing chemicals, he claimed to create rain over extensive areas. In 1916, Hatfield contracted with the city of San Diego to alleviate drought conditions and was to be paid \$1,000 for each inch of rain produced. When 20 inches of rain coincidentally fell nearby, the resulting floods destroyed a dam, killed 17 people, and produced millions of dollars damage. Hatfield, faced with a choice of assuming financial responsibility for the lawsuits or leaving the city without pay, chose the latter.³⁷

One of Hatfield's accomplices was a colorful racetrack reporter from New York, who met and joined Hatfield in California in 1912, named James Stuart Aloysius MacDonald, alias Colonel Stingo, "the Honest Rainmaker." Over his half-century career as a writer, mostly for various horseracing journals, MacDonald reportedly involved himself in various schemes for quick profit, including weather changing projects on both the west and east coasts. Contracts with clients were drawn up with terms for remuneration that resembled very much the language of success or failure at the racetrack. By his own admission, MacDonald based his odds for success on past weather data for a given area, which he obtained from records of the U.S. Weather Bureau or the New York Public Library.³⁸ MacDonald, or Colonel Stingo, was the inspiration for a Broadway play called "The Rainmaker" which opened in 1954.

DEVELOPMENT OF SCIENTIFIC FUNDAMENTALS

Espy's 1839 proposal for an experiment on the production of convection currents and water vapor condensation at high altitudes was

³⁴ Fernow, Bernhard E., in report to Jeremiah McClain Rusk, Secretary of Agriculture, 1891, as reported in Ward, "Artificial Rain; a Review of the Subject to the Close of 1889," 1892, p. 492.

³⁵ Byers, "History of Weather Modification," 1974, p. 5.

³⁶ Fleagle, "Background and Present Status of Weather Modification," 1968, p. 9.

³⁷ Halacy, "The Weather Changers," 1968, pp. 68-69.

³⁸ Liebling, A. J., "Profiles," *The New Yorker*, Sept. 20, 1952, pp. 45-71.

based on sound physical principles. Since knowledge of atmospheric processes was expanding and unfolding rapidly at the time, Hartman reminds us that the limited usefulness of Espy's weather modification concepts should not be ascribed to faulty logic, but rather to the primitive understanding at the time of the complex processes in precipitation, many of which are still not understood satisfactorily.³⁹

The understanding which meteorologists have today about precipitation has been learned slowly and sometimes painfully, and, while many of the discoveries have resulted from 20th century research, some important findings of the latter part of the 19th century are fundamental to these processes. Important results were discovered in 1875 by Coulier in France on foreign contaminant particles in the normal atmosphere, and quantitative measurements of the concentrations of these particles were achieved by Aitken in 1879. These events established a basis for explaining the fundamental possibility for occurrence of precipitation. Earlier, it had been learned that high supersaturations were required for the formation of water droplets.⁴⁰ Aitken was the first to imply that there are two types of nuclei, those with an affinity for water vapor (hygroscopic particles) and nuclei that require some degree of supersaturation in order to serve as condensation centers. The Swedish chemist-meteorologists of the 1920's developed a theory of condensation on hygroscopic nuclei and showed the importance of sea-salt particles. In the 1930's in Germany and the United Kingdom, a series of measurements were conducted on the numbers and sizes of condensation nuclei by Landsberg, Judge, and Wright. Data from measurements near Frankfurt, augmented subsequently by results from other parts of the world, have been adopted as the standard of reference for condensation nuclei worldwide.⁴¹

At the beginning of the 1930's important aspects of cloud physics were not yet understood. In particular, the importance of the ice phase to precipitation was not yet clarified, though, ever since the turn of the century meteorologists were aware that water droplets were abundantly present in clouds whose temperatures were well below the freezing point. Little was known about the microphysics of nucleation of ice crystals in clouds; however, it had been noted that rains fell only after visible glaciation of the upper parts of the clouds. Understanding of these processes was essential before scientific seeding of clouds for weather modification could be pursued rationally. In 1933 Tor Bergeron presented and promulgated his now famous theory on the initiation of precipitation in clouds containing a mixture of liquid and ice. W. Findeisen expanded on Bergeron's ideas and published a clearer statement of the theory in 1938; consequently, the concept is generally known as the Bergeron-Findeisen theory.⁴² In his investigation of the formation of ice crystals, Findeisen was of the opinion that they crystallized directly from the vapor (that is, by sublimation) rather than freezing from droplets. He also conjectured that quartz crystals might be the nuclei responsible for this process and even foresaw that the mechanism might be initiated artificially by introducing suitable nuclei.⁴³

³⁹ Hartman, "Weather Modification and Control," 1966, p. 13.

⁴⁰ *Ibid.*

⁴¹ Byers, "History of Weather Modification," 1974, p. 7.

⁴² *Ibid.*, p. 8.

⁴³ *Ibid.*, pp. 8-9.

Findeisen stated emphatically that rain of any importance must originate in the form of snow or hail, though Bergeron had admitted the occurrence of warm rain in the tropics. Though many meteorologists doubted that the ice crystal process was an absolute requirement for rain, they had been unable to collect evidence from aircraft observations. In Germany aerological evidence was obtained on the growth of rain drops by the collision-coalescence process in "warm" clouds, but the papers on this work were published in 1940, and World War II restricted communication of the results to meteorologists worldwide. Meanwhile in the United States, papers were published on the theory of the warm rain process. In 1938, Houghton showed that precipitation could be started by either the Bergeron process or by the collision-coalescence process. He noted that drops could be formed by condensation on "giant" hygroscopic nuclei present in the air and that growth of droplets to raindrop size was possible through collision. G. C. Simpson elucidated further on condensation and precipitation processes in 1941, disagreeing with Findeisen's rejection of "warm" rain formation by the collision-coalescence process.⁴⁴

EARLY CLOUD-SEEDING EXPERIMENTS

Starting about 1920 and continuing for about two decades until the outbreak of World War II, there were a number of experiments and operations intended to produce rain or modify the weather in some other way. Although some of these activities were pursued in a scientific manner, others were less so and were directed at producing immediate results; all of these projects lacked the benefit of the fundamental knowledge of precipitation processes that was to be gained later during this same period, the discoveries of which are discussed in the preceding subsection. Various schemes during this period included the dispensing of materials such as dust, electrified sand, dry ice, liquid air, and various chemicals, and even the old idea that explosions can bring rain. Field tests were conducted in the United States, Germany, the Netherlands, and the Soviet Union.

Byers tells about the experimental work of Dr. E. Leon Chaffee, professor of physics at Harvard, who became interested in the possibility of making cloud particles coalesce by sprinkling electrically charged sand over the clouds:

Dr. Chaffee became enthusiastic about the idea and developed in his laboratory a nozzle for charging sand and dispersing it from an airplane. The nozzle could deliver sand grains having surface gradients of the order of 1,000 V/cm. Flight experiments were carried out in August and September of 1924 at Aberdeen, Md., with an airplane scattering the sand particles in the clear air above clouds having tops at 5,000 to 10,000 feet. Dr. Chaffee reported "success" in the reverse sense, in that several clouds were observed to dissipate after treatment. The tests were well publicized in newspapers and scientific news journals, and this author, then a freshman at the University of California, recalls that his physics professors were enthusiastic about the idea. Chaffee's results probably would not endure the type of statistical scrutiny to which experiments of this kind are subject today.⁴⁵

Chaffee considered several trials successful, since clouds were dissipated after being sprayed with the charged sand. It has been pointed

⁴⁴ Ibid., p. 9.

⁴⁵ Ibid., p. 5.

out, however, in view of the much greater experience in recent years, that scientists must be extremely cautious in ascribing success in such experiments, when the evidence is based largely on visual observations.⁴⁶

In the Netherlands, August Veraart successfully produced rain by seeding clouds with dry ice from a small aircraft in 1930. This was 16 years before the work at General Electric in the United States, when clouds were also seeded with dry ice, initiating the modern period in the history of weather modification. Since Veraart probably did not understand the mechanism involved in the precipitation process which he triggered, he did not realize that the dry ice was effective in development of ice crystals by cooling supercooled clouds, and his success was likely only a coincidence. Byers observes that Veraart's vague concepts on changing the thermal structure of clouds, modifying temperature inversions, and creating electrical effects were not accepted, however, by the scientific community.⁴⁷ He claimed to be a true rain-maker and made wide, sweeping claims of his successes. He died in 1932, a year before Bergeron's theory appeared, not aware of the theoretical basis for his work.⁴⁸

Partly successful experiments on the dissipation of fog were conducted by the Massachusetts Institute of Technology in the 1930's, under the direction of Henry G. Houghton. At an airfield near Round Hill, Mass., fog was cleared using sprays of water-absorbing solutions, particularly calcium chloride, as well as fine particles of dry hygroscopic material. Results of these experiments, which predated some of the present-day fog dispersal attempts by some 30 years, were reported in 1938.⁴⁹

WEATHER MODIFICATION SINCE 1946

CHRONOLOGY

The following chronology of "critical events" relating to weather modification policy, compiled by Fleagle, unfolds only some of the major events and activity periods which have occurred since the historic discoveries of 1946:⁵⁰

1946: Schaefer demonstrated seeding with dry ice.

1947: Vonnegut demonstrated seeding with silver iodide.

1947-55: Irving Langmuir advertised weather modification widely and aggressively.

1947-53: General Electric field experiments ("Cirrus") extended evidence that clouds can be deliberately modified, but failed to demonstrate large effects.

1948-50: Weather Bureau Cloud Physics Project on cumulus and stratiform clouds resulted in conservative estimate of effects.

1948-52: Commercial operations grew to cover 10 percent of United States.

1950: Report of Panel on Meteorology of Defense Department's Research and Development Board (Haurwitz, Chairman) was adverse to Langmuir's claims.

1953: Public Law 83-256 established President's Advisory Committee on Weather Control.

⁴⁶ McDonald, James E., "An Historical Note on an Early Cloud-Modification Experiment." *Bulletin of the American Meteorological Society*, vol. 42, No. 3, March 1961, p. 195.

⁴⁷ Byers, "History of Weather Modification," 1947, p. 6.

⁴⁸ Hartman, "Weather Modification and Control," 1966, p. 15.

⁴⁹ Houghton, Henry G., and W. H. Radford, "On the Local Dissipation of Natural Fog." *Papers in Physical Oceanography and Meteorology*, Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, vol. 6, No. 3, Cambridge and Woods Hole, Mass., October 1938, 63 pp.

⁵⁰ Fleagle, Robert G., "An Analysis of Federal Policies in Weather Modification." Background paper prepared for use by the U.S. Department of Commerce Weather Modification Advisory Board, Seattle, Wash., March 1977, pp. 3-5.

1953-54: "Petterssen" Advisory Committee organized field tests on storm systems, convective clouds, and cold and warm fog (supported by the Office of Naval Research, the Air Force, the Army Signal Corps, and the Weather Bureau). These statistically controlled experiments yielded results which have been substantially unchanged in subsequent tests.

1957: Report of Advisory Committee (Orville, Chairman) concluded that tests showed 15 percent increase in orographic winter precipitation.

1957: Major cut in research support across the board by Defense Department sends major perturbation through research structure.

1958: Public Law 85-510 assigned lead agency responsibility to the National Science Foundation (NSF).

1959: Commercial operations had diminished to cover about one percent of the United States.

1961: First hurricane seeding under Project Stormfury.

1961: Bureau of Reclamation authorized by Congress to conduct research in weather modification.

1961: RAND report on weather modification emphasized complexity of atmospheric processes and interrelation of modification and prediction.

1962-70: Randomized field experiments established magnitude of orographic effects.

1964: Preliminary report of National Academy of Sciences/Committee on Atmospheric Sciences (NAS/CAS) roused anger of private operators and stimulated the evaluation of operational data.

1964-present: Department of the Interior pushed the case for operational seeding to augment water supplies.

1966: NAS/CAS report 1850 laid the basis for expanded Federal programs.

1966: Report of NSF Special Commission on Weather Modification and an NSF symposium called attention to social, economic, and legal aspects.

1966: Interdepartmental Committee for Atmospheric Sciences (ICAS) report (Newell, Chairman) proposed expanded Federal support to \$90 million by 1970.

1966-68: Efforts of the Departments of Commerce and Interior to gain lead agency status were unsuccessful.

1967: ICAS recommended that Commerce be designated as lead agency.

1967: S. 2916, assigning lead agency responsibility to the Department of Commerce; passed the Senate but did not become law.

1967-72: Military operational programs conducted in Vietnam.

1968: Public Law 90-407 removed the NSF mandate as lead agency.

1968: Detrimental effects of acid rain reported from Sweden.

1969: Public Law 91-190 (National Environmental Policy Act) required impact statements.

1970: Massachusetts Institute of Technology Study of Critical Environmental Problems called attention to inadvertent effects on climate.

1970: Stratospheric contamination by SST's suggested.

1971: Departments of Commerce and Interior carried out operational programs in Oklahoma and Florida.

1971: Public Law 92-205 required filing of reports of non-Federal weather modification activities with the Department of Commerce.

1971: International Study of Man's Impact on Climate raised this issue to international level.

1971: NAS/CAS report on priorities for the 1970's emphasized need for attention to management and policy problems of weather modification.

1971: Federal Council for Science and Technology approved seven national projects under various lead agencies.

1971-72: First technological assessments of weather modification projects are favorable to operational programs.

1971-74: Climate impact assessment program (CIAP) of Department of Transportation indicates potentially serious consequences of large SST fleet but suggests ways to ameliorate the problem.

1972: Failure of Soviet wheat crop and drought in Sahel emphasized critical need for understanding climate and the value of effective weather modification.

1973: Weather modification budget reduced by impoundment from \$25.4 million to \$20.2 million.

1973: Five national projects deferred or terminated.

1973: NAS/CAS report on weather and climate modification confirmed earlier conclusions and recommended lead agency status for NOAA.

1974: Stratospheric contamination by freon reported.

1974: Domestic Council organized panels in climate change and weather modification.

1974: General Accounting Office report on weather modification criticized weather modification program and pointed to need for lead agency.

1974: Defense Department released information on operations in Vietnam.

1974: The United States and the U.S.S.R. agreed to a joint statement intended "to overcome the dangers of the use of environmental modification techniques for military purposes."

1975: World Meteorological Organization Executive Committee proposed cumulus experiment perhaps in Africa or Iran.

1975: Department of Transportation CIAP report indicated that a fleet of 500 SST's would deplete ozone significantly, but suggested that cleaner engines could be developed.

1976: Chinese disapproval resulted in abandoning plans for Stormfury in the western Pacific.

1976: Hearings held on three weather modification bills by Senate Commerce Committee.

1976: The National Weather Modification Policy Act of 1976 (Public Law 94-859) enacted requiring study of weather modification.

1977: Exceptionally dry winter in the west stimulates State operational programs intended to increase mountain snowpack.

Since the completion of Fleagle's list above in March 1977, at least three other activities of equivalent significance ought to be noted:

1977: The U.S. Department of Commerce Weather Modification Advisory Board established in April 1977 and initiated a major study on a recommended national policy and Federal program of research in weather modification, in accordance with requirements to be fulfilled by the Secretary of Commerce under Public Law 94-490, the National Weather Modification Policy Act of 1976.

1977: The United Nations General Assembly approved a treaty banning environmental modification activities for hostile purposes on May 18, 1977; and the treaty opened for signature by the member nations.

1978: The Report of the Commerce Department's Weather Modification Advisory Board transmitted through the Secretary of Commerce to the Congress.

The history of the modern period of weather modification which follows is essentially that of the two decades following the monumental discoveries of 1946. An excellent account of the history of weather modification, which emphasizes this period, has been prepared by Byers.⁵¹ This work has been very helpful in some of the material to follow and is referenced frequently. The late 1960's and the 1970's are so recent that events during this period are discussed in various sections of the report as ongoing activities or events leading to current activities in weather modification research programs, operations, and policy decisions rather than in this chapter as an integral part of an updated history of the subject.

LANGMUIR, SCHAEFER, AND VONNEGUT

The modern era of scientific weather modification began in 1946, when a group of scientists at the General Electric Co. demonstrated that, through "seeding," a cloud of supercooled water droplets could be transformed into ice crystals and precipitation could be induced. These were not traditional meteorologists, though their leader, Dr. Irving Langmuir, was a famous physicist and Nobel laureate. He and his assistant, Vincent J. Schaefer, had been working for 3 years on cloud physics research, however, in which they were studying particle sizes, precipitation static, and icing. Their field research was carried on

⁵¹ Byers, "History of Weather Modification," 1974, pp. 3-44.

at the summit of Mt. Washington, N.H., where they observed supercooled clouds which often turned into snowstorms.⁵²

In an attempt to simulate field conditions, Schaefer contrived a laboratory setup using a home freezer lined with black velvet, with a light mounted so as to illuminate ice crystals that might happen to form in the box. Breathing into the box, whose temperature was about -23°C , produced fog but no ice crystals, even when various substances—including sand, volcanic dust, sulfur, graphite, talc, and salt—were dropped in as possible sublimation nuclei.⁵³ On July 12, 1946, Schaefer wanted to lower the freezer temperature somewhat, so he inserted a large piece of dry ice, and, in an instant, the air was full of millions of ice crystals. He discovered that even the tiniest piece of dry ice produced the same effect. In fact, dry ice had no direct effect on the supercooled cloud; producing an air temperature below -39°C was critical.⁵⁴

In his paper on the laboratory experiments, published in the November 15, 1946, issues of "Science" Schaefer stated:

It is planned to attempt in the near future a large-scale conversion of supercooled clouds in the atmosphere to ice crystal clouds, by scattering small fragments of dry ice into the cloud from a plane. It is believed that such an operation is practical and economically feasible and that extensive cloud systems can be modified in this way.⁵⁵

Two days before the paper appeared, on November 13, 1946, Schaefer made his historic flight, accomplishing man's first scientific seeding of a supercooled cloud, as he scattered three pounds of dry ice along a 3-mile line over a cloud to the east of Schenectady, N.Y. At 14,000 feet the cloud temperature was -20°C , and in about 5 minutes after seeding the entire cloud turned into snow, which fell 2,000 feet before evaporating.⁵⁶

Dr. Bernard Vonnegut had also worked on aircraft icing research and in 1946 at General Electric was pursuing a variety of nucleation problems; but, after Schaefer's laboratory experiments, he again turned his attention to ice nucleation research. He discovered that silver iodide and lead iodide had crystal structures close to that of ice and were also insoluble in water, and after repeated initial failures, owing to impurities in the material, Vonnegut was able to produce ice crystals, using very pure silver iodide powder, at temperatures only a few degrees below freezing. Soon means were developed for generating silver iodide smokes, and man's first successful attempt at artificial nucleation of supercooled clouds was accomplished.⁵⁷

Langmuir explained that dry ice could make ice crystals form by lowering the temperature to that required for natural nucleation on whatever might be present as nuclei, or even in the absence of all nuclei; however, the silver iodide provided a nucleus that was much more efficient than those occurring naturally.⁵⁸

⁵² *Ibid.*, pp. 9–10.

⁵³ Halacy, "The Weather Changers," 1968, pp. 82–83.

⁵⁴ Langmuir, Irving, "The Growth of Particles in Smoke, and Clouds and the Production of Snow from Supercooled Clouds," *Proceedings of the American Philosophical Society*, vol. 92, no. 3, July 1948, p. 182.

⁵⁵ Schaefer, Vincent J., "The Production of Ice Crystals in a Cloud of Supercooled Water Droplets," *Science*, vol. 104, No. 2707, Nov. 15, 1946, p. 459.

⁵⁶ Byers, "History of Weather Modification," 1974, p. 12.

⁵⁷ *Ibid.*, p. 13.

⁵⁸ Langmuir, Irving, "Cloud Seeding by Means of Dry Ice, Silver Iodide, and Sodium Chloride," *Transactions of the New York Academy of Sciences*, ser. II, vol. 14, November 1951, p. 40.

Following Schaefer's successful flight of November 13, 1946, and in the months and immediate years thereafter, Langmuir was quoted in the popular press as being very optimistic in his predicted benefits from weather modification. In a 1948 paper he said that "* * * it becomes apparent that important changes in the whole weather map can be brought about by events which are not at present being considered by meteorologists."⁵⁹ His publications and informal statements of this character touched off years of arguments with professional meteorologists, by whom refutation was difficult in view of Langmuir's standing in the scientific community. His enthusiasm for discussing the potential extreme effects from weather control was unrestrained until his death in 1957.⁶⁰

RESEARCH PROJECTS SINCE 1947

Project Cirrus

Although the business of the General Electric Co. had not been in meteorology, it supported the early research of Langmuir and his associates because of the obvious importance of their discoveries. Realizing that weather modification research was more properly a concern of the Federal Government, the company welcomed the interest of, and contract support from, the U.S. Army Signal Corps in February 1947. Subsequently, contract support was augmented by the Office of Naval Research, the U.S. Air Force provided flight support, and the U.S. Weather Bureau participated in a consultative role. The entire program which followed, through 1951, under this arrangement, including the field activities by Government agencies and the laboratory work and general guidance by General Electric, was designated "Project Cirrus."⁶¹ According to Byers:

The most pronounced effect produced by Project Cirrus and subsequently substantiated by a number of tests by others, was the clearing of paths through supercooled stratus cloud layers by means of seeding from an airplane with dry ice or with silver iodide. When such clouds were not too thick, the snow that was artificially nucleated swept all the visible particles out of the cloud. * * * In one of the first flights, * * * the supercooled particles in stratus clouds were removed using only 12 pounds of dry ice distributed along a 14-mile line. In later flights even more spectacular results were achieved, documented by good photography.⁶²

Initial Project Cirrus studies were made during the summer of 1947 on cumulus clouds near Schenectady, but the important seeding experiments were conducted the following year in New Mexico. Also during 1947, there was an attempt on October 13 to modify a hurricane east of Jacksonville, Fla., through seeding with dry ice.⁶³ Visual observations, reported by flight personnel, seemed to indicate a pronounced change in the cloud deck after seeding, and, shortly thereafter, the hurricane changed its course and headed directly westward, striking the coasts of Georgia and South Carolina. Even though there was precedent for such erratic behavior of hurricanes, there was speculation about the effect of seeding on the storm path, and the possibility of legal responsibility for damages which might be caused by

⁵⁹ Langmuir, Irving. "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures Above Freezing," *Journal of Meteorology*, vol. 5, No. 5, October 1948, p. 192.

⁶⁰ Byers, "History of Weather Modification," 1974, pp. 13-14.

⁶¹ *Ibid.*, p. 14.

⁶² *Ibid.*

⁶³ See discussion of Project Stormfury in ch. 5, p. 296 ff.

such experiments in the future provided reason to avoid seeding thereafter any storms with the potential of reaching land. The legal counsel of the General Electric Co. admonished Langmuir not to relate the course of the hurricane to the seeding; however, throughout the remainder of his career he spoke of the great benefit to mankind of weather control and of the potential ability to abolish evil effects of hurricanes. As a result, it was expected that the U.S. Weather Bureau would undertake massive efforts in weather control. Meteorologists within and without of the Bureau were in a defensive position, with many other scientists, impressed by Langmuir's arguments, opposing their position. Thus great controversies which developed between Langmuir and the Weather Bureau and much of the meteorological community followed these and other claims, and often resulted from the fact that Langmuir did not seem to fully comprehend the magnitude and the mechanisms of atmospheric phenomena.⁶⁴

Langmuir wanted to work where he thought storms originated rather than in upstate New York. He chose New Mexico as operations area for Project Cirrus, also taking advantage of the opportunity to collaborate there with Dr. E. J. Workman at the New Mexico Institute of Mining and Technology, whose thunderstorm research included radar observations and laboratory experiments on the effects of ice on storm electrification. After cloud-seeding flights there in October 1948, Langmuir reported that, as a result of the seeding, rainfall had been produced over an area greater than 40,000 square miles (about one-fourth the area of the State of New Mexico).⁶⁵

The Project Cirrus group returned to New Mexico in July 1949, and 10 additional seeding flights were conducted. When Langmuir learned that Vonnegut was dispensing silver iodide from a ground generator in the same area and had, in fact, also been doing so during the flights of the previous October, he concluded that both the July 1949 results and the widespread effects of October 1948 were caused by the silver iodide rather than the dry ice seeding as he had theorized previously. Spectacular results continued to be reported by him, spurred on by meteorologists' challenges to his statistical methods and conclusions. Noting that Vonnegut had operated the ground generator only on certain days, Langmuir observed that rainfall responses corresponded to generator "on" times, leading him to his controversial "periodic seeding experiment," to which the remainder of his life was devoted.⁶⁶

In the periodic seeding experiment, the silver iodide generators were operated in an attempt to effect a 7-day periodicity in the behavior of various weather properties. Langmuir was convinced that unusual weekly weather periodicities in early 1950 resulted from periodic seedings begun in New Mexico in December 1949, concluding that the effects were more widespread than he felt earlier and that temperatures and pressures thousands of miles away were also affected. Meteorologists observed that, while these correlations were the most striking seen, yet such periodicities were not uncommon.⁶⁷ The Weather Bureau undertook a study of records from 1919 to 1951 to see if such weather perio-

⁶⁴ *Ibid.*, pp. 14-16.

⁶⁵ *Ibid.*, p. 18.

⁶⁶ *Ibid.*, p. 19.

⁶⁷ *Ibid.*, pp. 19-20.

dicities had occurred in the past. Glenn W. Brier, author of the report on this study, indicated that a 7-day component in the harmonic analysis of the data appeared frequently, though seldom as marked as during the periodic seeding experiment.⁶⁸ Byers' opinion is that the evidence appeared just as reliable for occurrence of a natural periodicity as for one controlled artificially. He contends that the most important discoveries in cloud physics and weather modification were made in the General Electric Research Laboratory before Project Cirrus was organized, that the effect of clearing stratus decks was shown soon after the project was underway, and that the seeding experiments thereafter became more of a "program of advocacy than of objective proof." The project "* * * failed to demonstrate that seeding of cumulus clouds increased rainfall, that seeding initiates self-propagating storms, that the atmosphere responds periodically to periodic seeding, or that a hurricane could be deflected in its path by seeding."⁶⁹

Seeding under Project Cirrus ended in 1951 and the final report appeared in 1953. After the close of the project, Langmuir continued his analyses and wrote two more papers before his death in 1957. The final paper was titled "Freedom—the Opportunity To Profit From the Unexpected," a report that Byers feels provided a fitting philosophical close to his career.⁷⁰ The Defense Department sponsored another series of experiments, called the Artificial Cloud Nucleation Project, from 1951 to 1953.

The Weather Bureau Cloud Physics project

Amid increasing publicity and spectacular claims of results from cloud seeding in Project Cirrus, the U.S. Weather Bureau initiated in 1948 a project to test cloud seeding, with the cooperation of the National Advisory Committee for Aeronautics, the Navy, and the Air Force. The Cloud Physics Project, the first systematic series of seeding experiments in stratiform and cumuliform clouds, continued for 2 years, with flight operations in Ohio, California, and the Gulf States. Findings of Project Cirrus were substantiated in that striking visual cloud modifications occurred; however, there was no evidence to show spectacular precipitation effects, and the experiments led to a conservative assessment of the economic importance of seeding.⁷¹ Cloud dissipation rather than new cloud development seemed to be the general result from seeding, the only precipitation extractable from clouds was that contained in the clouds themselves, and cloud seeding methods did not seem to be promising for the relief of drought.⁷²

Results of the cloud physics experiment had almost no effect on the prevalent enthusiasm at the time for rainmaking through cloud seeding, except in the "hard core" of the meteorology community.⁷³ As a result of these experiments and the interpretation of the results, the Weather Bureau and its successor organizations in the Commerce Department, the Environmental Science Services Administration and the National Oceanic and Atmospheric Administration, have been

⁶⁸ Brier, Glenn W., "Seven-Day Periodicities in May 1952," *Bulletin of the American Meteorological Society*, vol. 35, No. 3, March 1954, pp. 118–121.

⁶⁹ Byers, "History of Weather Modification," 1974, pp. 20–21.

⁷⁰ *Ibid.*, p. 20.

⁷¹ Fleagle, Robert G., "Background and Present Status of Weather Modification," 1968, pp. 9–10.

⁷² Byers, "History of Weather Modification," 1974, pp. 16–17.

⁷³ *Ibid.*, p. 17.

regarded by some critics as unimaginative and overconservative on weather modification.⁷⁴

The U.S. experiments of 1953-54

In 1951 the Weather Bureau, the Army, the Navy, and the Air Force appointed an advisory group, chaired by Dr. Sverre Petterssen of the University of Chicago, under whose advice and guidance the following six weather modification projects were initiated:⁷⁵

1. Seeding of extratropical cyclones, sponsored by the Office of Naval Research and conducted by New York University.

2. Seeding of migratory cloud systems associated with fronts and cyclones, conducted by the Weather Bureau.

3. Treatment of convective clouds, supported by the Air Force and conducted by the University of Chicago.

4. Research on the dissipation of cold stratus and fog, conducted by the Army Signal Corps.

5. Studies of the physics of ice fogs, sponsored by the Air Force and conducted by the Stanford Research Institute.

6. Investigation of a special warm stratus and fog treatment system, sponsored by the Army and conducted by Arthur D. Little, Inc.

Field experiments on these projects were carried out in 1953 and 1954, and reports were published under the auspices of the American Meteorological Society in 1957.⁷⁶

The purpose of the extratropical cyclone seeding project, called Project Scud, was to " * * * ascertain whether or not it would be possible to modify the development and behavior of extratropical cyclones by artificial nucleation. * * * " ⁷⁷ Analysis obtained in Scud from Florida to Long Island showed that " * * * the seeding in this experiment failed to produce any effects which were large enough to be detected against the background of natural meteorological variance. " ⁷⁸

The Weather Bureau project on migratory cloud systems was conducted in western Washington on cloud systems that enter the area from the Pacific during the rainy winter months. This project was criticized by commercial seeders since it was conducted in the West, which was considered "their territory," and by those who accused the Weather Bureau of seeking a negative result to support their conservative view toward weather modification. Byers feels that there was an attempt to avoid this negative impression by giving a more positive interpretation to the results than the data possibly justified.⁷⁹ In summarizing results, Hall stated:

Considering the results as a whole there is no strong evidence to support a conclusion that the seeding produced measurable changes in rainfall. * * * the evaluations do not necessarily furnish information on what the effect might have been with more or less intense seeding activity, rate of release of dry ice, etc. Also it

⁷⁴ Fleagle, "Background and Present Status of Weather Modification," 1968, p. 10.

⁷⁵ Byers, "History of Weather Modification," 1974, p. 25.

⁷⁶ Petterssen, Sverre, Jerome Spar, Ferguson Hall, Roscoe R. Braham, Jr., Louis J. Battan, Horace R. Byers, H. J. aufm Kampe, J. J. Kelly, and H. K. Weickmann, "Cloud and Weather Modification: a Group of Field Experiments," Meteorological Monographs, vol. 2, No. 11. American Meteorological Society, Boston, 1957, 111 pp.

⁷⁷ Petterssen, Sverre, "Reports on Experiments with Artificial Cloud Nucleation: Introductory Note," In Petterssen et al., "Cloud and Weather Modification: a Group of Field Experiments," Meteorological Monographs, vol. 2, No. 11. American Meteorological Society, Boston, 1957, p. 3.

⁷⁸ Spar, Jerome, "Project Scud," In Petterssen et al., "Cloud and Weather Modification: a Group of Field Experiments," Meteorological Monographs, vol. 2, No. 11. American Meteorological Society, Boston, 1957, p. 22.

⁷⁹ Byers, "History of Weather Modification," 1974, p. 26.

might be speculated that the seeding increased rainfall on some occasions and decreased it on others.⁸⁰

The aim of the University of Chicago Cloud Physics project was as follows:⁸¹

The formulation of a consistent and immediately applicable picture of the processes of formation of cumulus clouds, charged centers, and precipitation with a view toward testing the possibility that one can modify these processes and influence the natural behavior of clouds.

So that as many cumulus clouds as possible could be tested, work was conducted in the Middle West in the summer and in the Caribbean in the winter, realizing that the warm trade-wind cumulus clouds in the latter region might be amenable to seeding with large hygroscopic nuclei or water spray, and that the ice-crystal process would operate to initiate precipitation in the colder clouds of the Middle West.⁸² Of the numerous conclusions from this project⁸³ a few will serve to indicate the value of the project to the understanding of cloud phenomena and weather modification. In the Caribbean tests, water spray from an aircraft was seen to increase rainfall as determined by radar echoes; analysis showed that the treatment doubled the probability of occurrence of a radar echo in a cloud. From tests on dry ice seeding in the Middle West it was found that in the majority of cases treated clouds showed an echo, while untreated ones did not, although the sample was considered too small to be significant. In all cases clouds were considered in pairs, one treated by seeding and the other untreated, and only those clouds showing no echo initially were chosen for study.⁸⁴

The seeding experiments with supercooled stratus clouds by the Army Signal Corps essentially substantiated the results of Project Cirrus; however, from these carefully conducted tests a number of new relationships were observed with regard to seeding rates, spread of glaciating effect, cloud thickness, overseeding, and cloud formation after seeding.⁸⁵ The report on this project carefully summarized these relationships and conclusions for both dry ice and silver iodide seeding.⁸⁶

The Air Force project on the physics of ice fogs, conducted by Stanford Research Institute, was intended to learn the relationship to such fogs of synoptic situations, local sources of water, and pollution. Investigations in Alaska at air bases showed that most fogs developed from local sources of water and pollution. In the Arthur D. Little investigation for the Army attempts were made to construct generators which were capable of producing space charges, associated with aerosols, that could bring about precipitation of the water droplets in warm fogs and stratus.⁸⁷

⁸⁰ Hall, Ferguson, "The Weather Bureau ACN Project." In Petterssen et al., "Cloud and Weather Modification; a Group of Field Experiments," Meteorological Monographs, vol. 2, No. 11. American Meteorological Society, Boston, 1957, pp. 45-46.

⁸¹ Braham, Roscoe R., Jr., Louis J. Battan, and Horace R. Byers, "Artificial Nucleation of Cumulus Clouds." In Petterssen et al., "Cloud and Weather Modification; a Group of Field Experiments," 1957, p. 47.

⁸² Byers, "History of Weather Modification," 1974, pp. 26-27.

⁸³ Conclusions are precisely spelled out in somewhat technical terms in: Braham, Battan, and Byers, "Artificial Nucleation of Cumulus Clouds," 1957, pp. 82-83.

⁸⁴ Byers, "History of Weather Modification," 1974, p. 27.

⁸⁵ Ibid.

⁸⁶ aufm Kampe, H. J., J. J. Kelly, and H. K. Weickmann, "Seeding Experiments in Subcooled Stratus Clouds." In Petterssen et al., "Cloud and Weather Modification; a Group of Field Experiments," Meteorological Monographs, vol. 2, No. 11. American Meteorological Society, Boston, 1957, p. 93.

⁸⁷ Petterssen, "Reports on Experiments With Artificial Cloud Nucleation: Introductory Note," 1957, p. 4.

Byers, in retrospect, wonders why the results of this series of six experiments, which were carefully controlled statistically, did not receive more attention than was accorded them. He attributes some of this lack of visibility to the publication in the somewhat obscure monograph of the American Meteorological Society⁸⁸ and to the delay in publishing the results, since the Petterssen committee held the manuscripts until all were completed, so that they could be submitted for publication together.⁸⁹

Arizona mountain cumulus experiments

After 1954, the University of Chicago group joined with the Institute of Atmospheric Physics at the University of Arizona in seeding tests in the Santa Catalina Mountains in southern Arizona. These experiments were conducted in two phases, from 1957 through 1960 and from 1961 through 1964, seeding mostly summer cumulus clouds, but some winter storms, with silver iodide from aircraft. In the first phase, analysis of precipitation data from the first 2 years revealed more rainfall during seeded than on nonseeded days; however, during the latter 2 years, considerably more rainfall was achieved on nonseeded days. Combining all data for the 4 years of the first phase yielded overall results with more rain on unseeded days than on seeded days; hence, the experiments were modified and the second phase undertaken. Of the 3 years in the second phase, only one showed more rain on seeded days than on nonseeded ones. None of the analyses attempted could support the hypothesis that airborne silver iodide seeding increased precipitation or influenced its areal extent. Byers suggests that the failure to increase rainfall may have been due to the fact that precipitation initiation resulted from the coalescence process rather than the ice-crystal process.⁹⁰

Project Whitetop

According to Byers, perhaps the most extensive and most sophisticated weather modification experiment (at least up to the time of Byers' historical review in 1973) was a 5-year program of summer convective cloud seeding in south-central Missouri, called Project Whitetop. Conducted from 1960 through 1964 by a group from the University of Chicago, led by Dr. Roscoe R. Braham, the purpose of Whitetop was to settle with finality the question of whether or not summer convective clouds of the Midwest could be seeded with silver iodide to enhance or initiate precipitation. Experimental days were divided into seeding and no seeding days, chosen randomly from operational days suitable for seeding, based on certain moisture criteria. Another feature of the project was the attempt to determine the extent of spreading of silver iodide smoke plumes from the seeding line. Precipitation effects were evaluated by radar and by a rain-gage network.⁹¹

Final analysis of all of the Project Whitetop data showed that the overall effect was that, in the presence of silver iodide nuclei, the rainfall was less than in the unseeded areas. Byers attributes these negative

⁸⁸ Petterssen et al., "Cloud and Weather Modification; a Group of Field Experiments," 1957.

⁸⁹ Byers, "History of Weather Modification," 1974, p. 28.

⁹⁰ *Ibid.*, p. 29.

⁹¹ *Ibid.*, pp. 29-30.

results to the physical data obtained from cloud-physics aircraft. "Most of the Missouri clouds produced raindrops by the coalescence process below the freezing line, and these drops were carried in the updrafts and frozen as ice pellets at surprisingly high subfreezing temperatures (-5°C to -10°C)." He further points out that the measured concentrations of ice particles, for the range of sizes present, were already in the natural unseeded conditions equivalent to those hoped for with seeding; consequently, the silver iodide only had the effect of over-seeding.⁹²

Climax experiments

Following the initial General Electric experiments, it was concluded by Bergeron⁹³ that the best possibility for causing considerable rainfall increase by artificial means might be found in seeding orographic⁹⁴ cloud systems. Consequently, there were almost immediate efforts to increase orographic precipitation, the greatest concentration of such work being in the Western United States. Commercial groups such as power companies and irrigation concerns took the early initiative in attempts to augment snowfall from orographic cloud systems in order to increase streamflow from the subsequent snowmelt.

Colorado State University (CSU) began a randomized seeding experiment in the high Rocky Mountains of Colorado in 1960, under the direction of Lewis O. Grant, to investigate snow augmentation from orographic clouds. The project was designed specifically to (1) evaluate the potential, (2) define seedability criteria, and (3) develop a technology for seeding orographic clouds in central Colorado.⁹⁵ It followed the 1957 report of the President's Advisory Committee for Weather Control, in which it had been concluded that seeding of orographic clouds could increase precipitation by 10 to 15 percent, basing this judgment, however, on data from a large number of seeding programs that had not been conducted on a random basis.⁹⁶

The first group of the CSU seeding experiments took place from 1960 to 1965 in the vicinity of Climax, Colo., and has been designated Climax I. A second set of tests in the same area from 1965 to 1970 has been referred to as Climax II. The Climax experiments are important in the history of weather modification because they were the first intensive projects of their kind and also because positive results were reported.⁹⁷ The precipitation for all seeded cases was greater than for all of the unseeded cases by 9, 13, and 39 percent, respectively, for Climax I, Climax II, and Climax IIB. The latter set of data are a subsample of those from Climax II, from which possibly contaminated cases due to upwind seeding by other groups were eliminated.⁹⁸

⁹² *Ibid.*, p. 30.

⁹³ Bergeron, Tor, "The Problem of an Artificial Control of Rainfall on the Globe; General Effects of Ice Nuclei in Clouds." *Tellus*, vol. 1, No. 1, February 1949, p. 42.

⁹⁴ A definition of orographic clouds, a discussion of their formation, and a summary of attempts to modify them are found in ch. 3, p. 71 ff.

⁹⁵ Grant, Lewis O., and Archie M. Kahan, "Weather Modification for Augmenting Orographic Precipitation." In Wilmot N. Hess (editor), "Weather and Climate Modification," New York, Wiley, 1974, p. 295.

⁹⁶ Advisory Committee on Weather Control. Final Report of the Advisory Committee on Weather Control, Washington, D.C., U.S. Government Printing Office, Dec. 31, 1957, vol. I, p. vi. (The establishment of the Advisory Committee and its activities leading to publication of its final report are discussed in ch. 5, under activities of the Congress and of the executive branch of the Federal Government, see pp. 195, 214, and 236.)

⁹⁷ Byers, "History of Weather Modification," 1974, pp. 30-31.

⁹⁸ Grant and Kahan, "Weather Modification for Augmenting Orographic Precipitation," 1974, p. 298.

Lightning suppression experiments

From 1947 until the close of Project Cirrus, interspersed with his other activities, Vincent Schaefer visited U.S. Forest Service installations in the northern Rockies in order to assist in attempts to suppress lightning by cloud seeding. As early as 1949 an attempt was made to seed thunderstorm clouds with dry ice, dumping it from the open door of a twin-engine aircraft flying at 25,000 feet.⁹⁹ This stimulated curiosity among those involved, but also showed that lightning-prevention research would require a long and carefully planned effort. These early activities led to the formal establishment of Project Skyfire in 1953, aimed at lightning suppression, as part of the overall research program of the Forest Service. Throughout the history of the project, research benefited from the cooperation and support of many agencies and scientific groups, including the National Science Foundation, the Weather Bureau, Muntalp Foundation, the Advisory Committee on Weather Control, the National Park Service, General Electric Research Laboratories, Meteorology, Inc., and several universities. The project was phased out by the Forest Service in the 1970's, since results of years of tests were inconclusive, although there had been some reports of success. Skyfire was the longest continuing Federal weather modification research project, enduring for about 20 years.¹

Fog dispersal research

Experiments were conducted on clearing supercooled fog from runways at Orly Airport in Paris since 1962, using sprays of liquid propane. Soon after these successful tests, the method became operational and has already succeeded in various U.S. Air Force installations. The dissipation of cold fog is now operational also at many locations, including some in North America and in the Soviet Union. Warm fogs, however, are more common over the inhabited globe, and efforts to dissipate them had not advanced very far, even by 1970.²

Hurricane modification

In an earlier discussion of the work of Langmuir and his associates under Project Cirrus, an attempt at hurricane modification was mentioned.³ The historical unfolding of hurricane research in the United States thereafter will not be reported here since it is discussed in detail in chapter 5, under Project Stormfury, now a major weather modification research program of the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce.⁴

Hail suppression

The principal lead in research to suppress hail during the 1950's and 1960's was not in the United States, but mainly elsewhere, particularly in Switzerland, France, Italy, the U.S.S.R., Argentina, Bulgaria, Yugoslavia, Kenya, and Canada. Hail suppression is based on the

⁹⁹ Barrows, J. S., "Preventing Fire from the Sky." In U.S. Department of Agriculture, "The Yearbook of Agriculture, 1968: Science for Better Living." Washington, D.C., U.S. Government Printing Office, 1968, p. 219.

¹ For a more detailed discussion of Project Skyfire, see p. 309, under the weather modification program of the Department of Agriculture in ch. 5.

² Byers, "History of Weather Modification," 1974, p. 33.

³ See p. 39.

⁴ See p. 296.

hypothesis that, if a cloud is supplied with a superabundance of ice nuclei, the available water will be used to form a great number of snow crystals, thus depriving the hailstones of sufficient water to grow to damaging size. Most of the early foreign attempts to suppress hail using explosive rockets or ground-based silver iodide generators proved disappointing.⁵

In the Soviet Union, the Caucasus hail suppression experiments of the mid-1960's were of great interest to cloud physicists. Using radar to locate the zone of greatest water content in convective clouds and rockets with explosive warheads to deliver lead iodide with precision into this zone, the Russians claimed success in suppressing hailstorms, based on statistical reduction in crop damages. Operational hail suppression activity is now conducted on a large scale in the Soviet Union.^{6, 7} Most hail suppression efforts in the United States in the 1960's were commercial operations which did not produce data of any significant value for further analysis.

Foreign weather modification research

While the Russians and some other countries have concentrated on hail suppression research, Australia, like the United States, has been principally concerned with augmenting precipitation. Very shortly after Schaefer first seeded a natural cloud with dry ice, Krauss and Squires of the Australian Weather Bureau seeded stratonimbus clouds in February 1947 near Sidney. The Commonwealth Scientific and Industrial Research Organization (CSIRO) subsequently organized, under Dr. E. G. Bowen, what might then have been the world's outstanding group of cloud physics and weather modification scientists. Byers feels that probably "* * * no other group contributed more to practical cloud physics during the period approximately from 1950 to 1965."⁸

The Snowy Mountain project in Australia, whose object was to produce a significant precipitation increase over the mountains by silver iodide seeding, has attracted most attention. For a 5-year period from 1955 through 1959, this experiment was conducted during the colder part of the Southern Hemisphere year, using silver iodide dispensed from aircraft. Although initial experimental reports indicated successful increases in precipitation over the target, the final 1963 report after complete analysis stated that results were encouraging but inconclusive.⁹

Interesting experiments were carried out in Israel during the 1960's, using airborne silver iodide seeding of mostly cumulus clouds. Statistical analysis of data from the first 5½ years of tests revealed an increase of 18 percent in rainfall.¹⁰

A project called Grossversuch III was conducted on the southern slopes of the Alps in Switzerland. Although initiated as a randomized hail suppression experiment, using ground-based silver iodide generators, the analysis indicated that hail frequency was greater on

⁵ Byers, "History of Weather Modification," pp. 31-32.

⁶ Ibid., p. 32.

⁷ The hail suppression efforts of the U.S.S.R. are discussed in more detail under the status of hail suppression technology in ch. 3, p. 88, and under foreign programs in ch. 9, 412.

⁸ Byers, "History of Weather Modification," 1974, p. 23.

⁹ Ibid., pp. 23-24.

¹⁰ Ibid., p. 31.

seeded than on nonseeded days, but that the average rainfall on seeded days was 21 percent greater than on nonseeded days.¹¹

COMMERCIAL OPERATIONS

In the weeks and months following Schaefer's first cloud seeding experiment public interest grew, and Langmuir and Schaefer spoke before and consulted with groups of water users, farmers and ranchers, city officials, Federal program directors, and scientific societies. As a result there was a burgeoning of new cloud-seeding efforts initiated by commercial operators, industrial organizations, water districts, and groups of farmers. Some used ground generators for dispensing silver iodide obviating the need for airplanes and their attendant high costs, so that many such operations became quite profitable. Many rain-makers were incompetent and some were unscrupulous, but their activities flourished for a while, as the experiments of Schaefer and Langmuir were poorly imitated. Some of the more reliable companies are still in business today, and their operations have provided data valuable to the development of weather modification technology.¹²

Byers relates a few instances of early commercial operations of particular interest.¹³ In 1949-50 the city of New York hired Dr. Wallace E. Howell, a former associate of Langmuir, to augment its water supply by cloud seeding. New York's citizenry became interested and involved in discussions over Howell's activities as the news media made them known. This project was also the first case where legal action was taken against cloud seeding by persons whose businesses could be adversely affected by the increased rain. Although rains did come and the city reservoirs were filled, Howell could not prove that he was responsible for ending the drought.¹⁴ Howell subsequently seeded in Quebec in August 1953 in an attempt to put out a forest fire and in Cuba to increase rainfall for a sugar plantation owner.¹⁵

The Santa Barbara project in California, also a commercial operation designed to increase water supply, received a great deal of attention. In this period water was increased through augmenting rain and snow in the mountains north and northeast of the city. The project was evaluated by the California State Water Resources Board and was unique among commercial contract operations, inasmuch as the clients permitted randomization (that is, random selection of only some storms for seeding) in order to allow adequate evaluation.¹⁶

In the West the earliest commercial operations were developed under Dr. Irving P. Krick, formerly head of the Department of Meteorology at the California Institute of Technology. Asked to monitor aerial dry ice seeding over Mt. San Jacinto in 1947, Krick became interested in weather modification, left Caltech, and formed his own company. Seeding projects were carried out during 1948 and 1949 for ranchers in San Diego County, Calif., in Mexico, and in Arizona. In 1950 he moved to Denver and formed a new company, which began seeding activity over the Great Plains, elsewhere in the West, and in

¹¹ *Ibid.*

¹² *Ibid.*, pp. 17, 21, 22.

¹³ *Ibid.*, pp. 22-23.

¹⁴ *Ibid.*, p. 22.

¹⁵ Halacy, "The Weather Changers," 1968, pp. 96-97.

¹⁶ *Ibid.*, pp. 22-23.

other countries. A number of former students of Krick joined him or formed other cloud seeding companies, mostly in the West during the 1950's.¹⁷ By 1953 Krick had operated 150 projects in 18 States and 6 foreign countries and amassed over 200,000 hours of seeding time. For three winters—1949, 1950, and 1951—his company claimed that they had increased the snowpack in the Rockies around Denver from 175 to 288 percent over the average of the previous 10 years. After 6 months of seeding in Texas in 1953, the water in a drainage basin near Dallas had increased to 363 percent of the January 1 level, while in nearby nonseeded basins water ranged from a 22-percent deficit to an increase of 19 percent.¹⁸

At the start of extensive seeding in the early 1950's there was a sharp increase in commercial operations, accompanied by great publicity as drought began in the Great Plains. During the middle and latter 1950's, however, seeding diminished as did the drought. The some 30 annual seeding projects in the United States during the mid and latter 1950's and the 1960's (excluding fog clearing projects) were conducted for the most part by about five firms, on whose staffs there were skilled meteorologists, cloud physicists, and engineers for installing and maintaining ground and air systems. Most of these projects were in the categories of enhancing rain or snowfall, with a distribution in a typical year as follows: About a dozen in the west coast States, half a dozen in the Rocky Mountains-Great Basin area, half a dozen in the Great Plains, and the remainder in the rest of the United States. Of the projects in the West, six to nine have been watershed projects sponsored by utility companies. Most of these projects endured for long periods of years and many are still underway.¹⁹

Fleagle notes that by the early 1950's, 10 percent of the land area of the United States was under commercial seeding operations and \$3 million to \$5 million was being expended annually by ranchers, towns, orchardists, public utilities, and resort operators. The extent of such commercial operations receded sharply, and by the late 1950's business was only about one-tenth or less than it had been a decade earlier. As noted above, public utilities were among those who continued to sponsor projects throughout this period.²⁰

Figure 1 shows the purposes of weather modification operations for various sections of the United States for the period July 1950 through June 1956. For each geographical section the column graphs represent the percentage of the total U.S. seeding for each of five purposes that was performed in that section. The bar graph in the inset shows the percentage of total U.S. cloud-seeding effort that is undertaken for each of these five purposes. Figure 2 shows the total area coverage and the percent of U.S. territory covered by cloud seeding for each year from July 1950 through June 1956. Both figures are from the final report of the President's Advisory Committee on Weather Control.²¹

¹⁷ Elliott, Robert D. "Experience of the Private Sector," 1974, p. 47.

¹⁸ Halacy, "The Weather Changers," 1968, p. 96.

¹⁹ Elliott, "Experience of the Private Sector," 1974, p. 46-48.

²⁰ Fleagle, "Background and Present Status of Weather Modification," 1968, p. 11.

²¹ Advisory Committee on Weather Control, Final Report, 1958, vol. II. Figures facing p. 242 and 243.

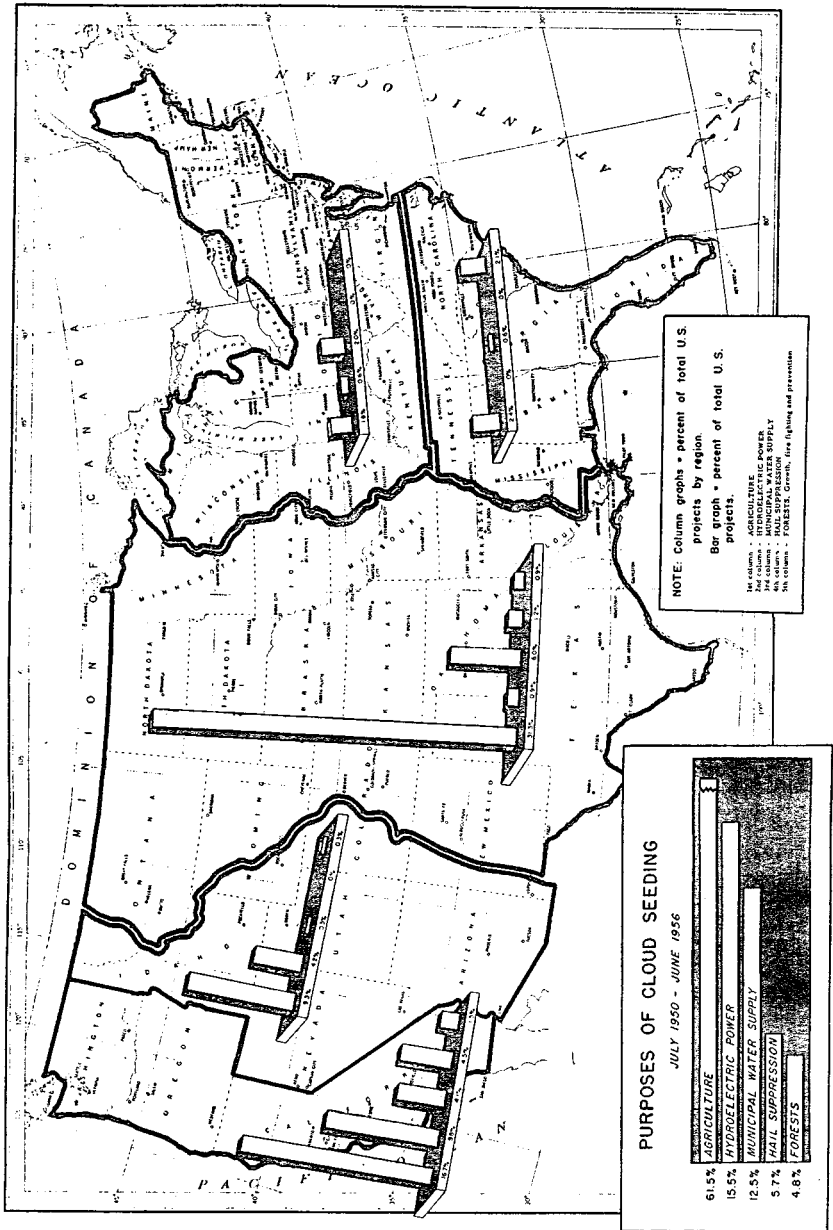


FIGURE 1.—Purposes of weather modification operations conducted in various geographical sections of the United States, July 1950 through June 1956. (From Final Report of the Advisory Committee on Weather Control, 1958.)

CLOUD SEEDING IN THE UNITED STATES

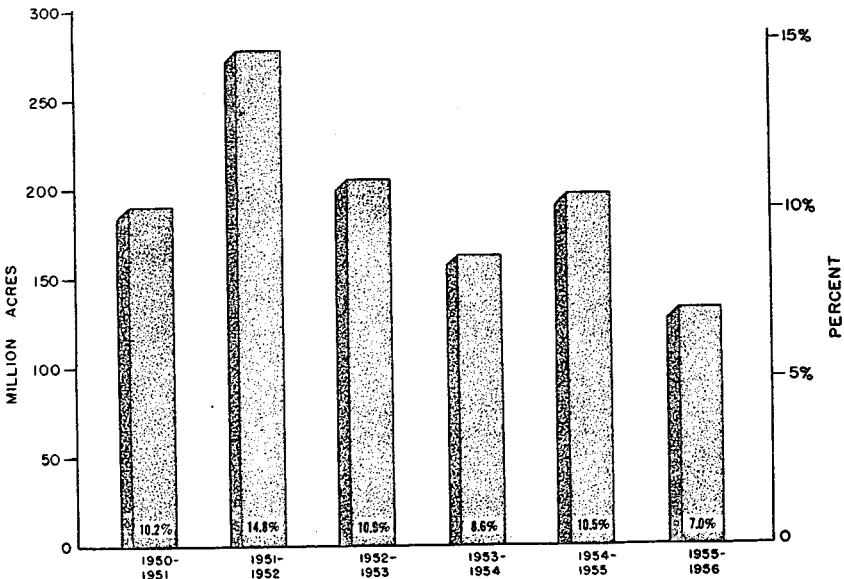


FIGURE 2.—Total area coverage and percent of area coverage for the 48 coterminous States of the United States by weather modification operations for each year, July 1950 through June 1956. (From Final Report of the Advisory Committee on Weather Control, 1958.)

Table 1 is a summary of weather modification operations for fiscal years 1966, 1967, and 1968, compiled by the National Science Foundation from field operators' reports which the Foundation required to be filed. Figure 3 shows the locations in the continental United States for both operational and research weather modification projects during fiscal year 1968. In September 1968, as provided by Public Law 90-407, the National Science Foundation was no longer authorized to require the submission of reports on operational weather modification projects.²² Weather modification activities are now reported to the Department of Commerce, under provisions of Public Law 92-205, and summary reports of these activities are published from time to time.²³

²² See discussions of this law and of the activities of the National Science Foundation as lead weather modification agency through September 1968, pp 196 and 215 in ch. 5.

²³ See discussions of Public Law 92-205 and of the weather modification activities reporting program in ch. 5, 197 and 232. The activities summarized in the latest available Department of Commerce report are discussed in ch. 7 and listed in app. G.

TABLE 1.—SUMMARY OF WEATHER MODIFICATION ACTIVITIES FROM FIELD OPERATORS' REPORTS, FISCAL YEARS 1966, 1967, AND 1968¹ (FROM NSF TENTH ANNUAL REPORT OF WEATHER MODIFICATION, 1968)

Purpose	Area treated (square miles)			Number of projects			Number of States ²			Number of operators ²		
	1966	1967	1968	1966	1967	1968	1966	1967	1968	1966	1967	1968
Rain augmentation and snow- pack increase.....	61,429	62,021	53,369	35	41	37	21	20	21	22	25	23
Hail suppression.....	20,566	20,556	13,510	3	4	4	3	3	5	3	4	4
Fog dissipation.....	100	118	145	22	15	15	15	13	9	17	15	10
Cloud modification.....	19,345	28,300	18,600	9	18	8	8	12	7	8	14	6
Lightning suppression.....	314	314	314	1	1	1	1	1	1	1	1	1
Totals.....	101,744	111,383	85,938	70	79	65	30	23	25	46	44	37

¹ Data for fiscal year 1968 include reports received to Sept. 1, 1968.² Totals are not the sum of the items since many States and operators are involved in more than one type of activity.

An early commercial hail suppression project was begun in Colorado in 1958. Eventually it involved 5 seeding aircraft and about 125 ground-based generators, making it the largest single cloud-seeding project up to that time. Results of the project were examined at Colorado State University and presented at the International Hail Conference in Verona, Italy, in 1960. This project stimulated the interest of scientists and provided historical roots for what later was established as the National Hail Research Experiment in the same area over a decade later by the National Science Foundation.^{24, 25}

During the 1960's, clearing of cold airport fog through cloud seeding became an operational procedure. Since the techniques used can only be applied to cold fog, they were used at the more northerly or high-altitude airports of the United States, where about 15 such projects were conducted, and are still underway, each winter.²⁶

²⁴ Elliott, "Experience of the Private Sector," 1974, p. 48.²⁵ The National Hail Research Experiment is discussed in detail under the weather modification program of the National Science Foundation in ch. 5; see p. 274ff.²⁶ Elliott, "Experience of the Private Sector," 1974, pp. 48-49.

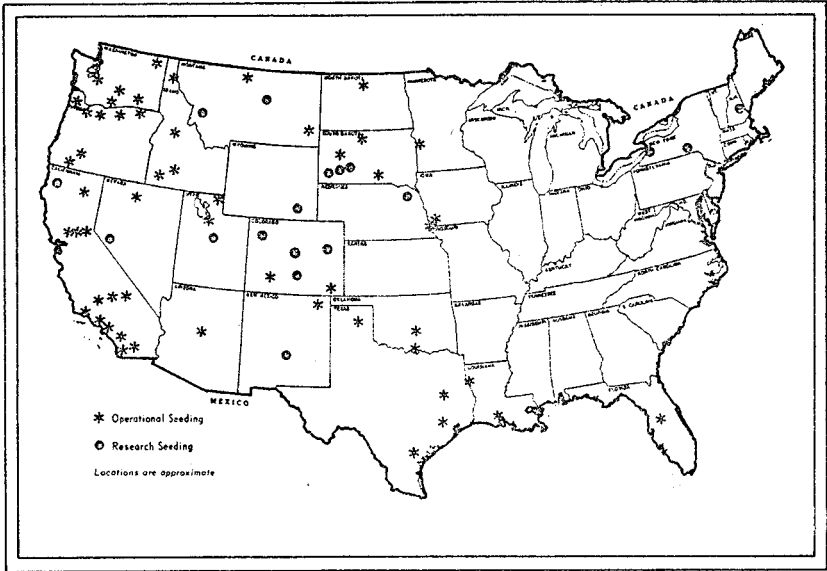


FIGURE 3.—Weather modification projects in the United States during fiscal year 1968. (From NSF Tenth Annual Report on weather modification, 1968.)

HISTORY OF FEDERAL ACTIVITIES, COMMITTEES, POLICY STUDIES, AND REPORTS

In the various discussions under activities of the Congress and the executive branch of the Federal Government in chapter 5, there are historical accounts of legislative actions pertinent to weather modification, of the establishment and functioning of special committees in accordance with public laws or as directed by the executive agencies, and of the policy and planning studies and reports produced by the special committees or by the agencies. Inclusion of a separate historical account of these Federal activities at this point would be largely repetitive, and the reader is referred to the various sections of chapter 5, in which historical developments of various Federal activities are unfolded as part of the discussions of those activities.

CHAPTER 3

TECHNOLOGY OF PLANNED WEATHER MODIFICATION

(By Robert E. Morrison, Specialist in Earth Sciences, Science Policy Research Division, Congressional Research Service)

INTRODUCTION

Although the theoretical basis for weather modification was laid to a large extent during the 1930's, the laboratory and field experiments which ushered in the "modern era" occurred in 1946 and in the years immediately thereafter. By 1950, commercial cloud seeding had become widespread, covering an estimated total U.S. land area of about 10 percent.¹ By the mid-1950's, however, it was apparent that the fundamental atmospheric processes which come into play in weather modification are very complex and were far from being understood. A period of retrenchment and reevaluation began, the number of commercial operators had decreased dramatically, and weather modification had fallen into some disrepute among many meteorologists and much of the public. A period of carefully designed experiments was initiated about two decades ago, supported by increased cloud physics research and increasingly more sophisticated mathematical models and statistical evaluation schemes.

Meanwhile, a small group of commercial operators, generally more reliable and more responsible than the typical cloud seeder of the 1950 era, has continued to provide operational weather modification services to both public and private sponsors. These operators have attempted to integrate useful research results into their techniques and have provided a bank of operational data useful to the research community. The operational and research projects have continued over the past two decades, often in a spirit of cooperation, not always characteristic of the attitudes of scientists and private operators in earlier years. Often the commercial cloud seeders have contracted for important roles in major field experiments, where their unique experiences have been valuable assets.

Through the operational experiences and research activities of the past 30 years, a kind of weather modification technology has been emerging. Actually, though some practices are based on common theory and constitute the basic techniques for meeting a number of seeding objectives, there are really a series of weather modification technologies, each tailored to altering a particular atmospheric phenomenon and each having reached a different state of development and operational usefulness. At one end of this spectrum is cold fog clearing, considered to be operational now, while the abatement of severe storms, at

¹ Fleagle, Robert G., "Background and Present Status of Weather Modification." In "Weather Modification: Science and Public Policy," Seattle, University of Washington Press, 1968, p. 11.

the other extreme, remains in the initial research phase. Progress to date in development of these technologies has not been nearly so much a function of research effort expended as it has depended on the fundamental atmospheric processes and the ease by which they can be altered. There is obvious need for further research and development to refine techniques in those areas where there has been some success and to advance technology where progress has been slow or at a virtual standstill.

ASSESSMENT OF THE STATUS OF WEATHER MODIFICATION TECHNOLOGY

Recently, the following summary of the current status of weather modification technology was prepared by the Weather Modification Advisory Board:

1. The only routine operational projects are for clearing cold fog. Research on warm fog has yielded some useful knowledge and good models, but the resulting technologies are so costly that they are usable mainly for military purposes and very busy airports.

2. Several long-running efforts to increase winter snowpack by seeding clouds in the mountains suggest that precipitation can be increased by some 15 percent over what would have happened "naturally."

3. A decade and a half of experience with seeding winter clouds on the U.S. west coast and in Israel, and summer clouds in Florida, also suggest a 10- to 15-percent increase over "natural" rainfall. Hypotheses and techniques from the work in one area are not directly transferable to other areas, but will be helpful in designing comparable experiments with broadly similar cloud systems.

4. Numerous efforts to increase rain by seeding summer clouds in the central and western parts of the United States have left many questions unanswered. A major experiment to try to answer them—for the High Plains area—is now in its early stages.

5. It is scientifically possible to open holes in wintertime cloud layers by seeding them. Increasing sunshine and decreasing energy consumption may be especially relevant to the northeastern quadrant of the United States.

6. Some \$10 million is spent by private and local public sponsors for cloud-seeding efforts, but these projects are not designed as scientific experiments and it is difficult to say for sure that operational cloud seeding causes the claimed results.

7. Knowledge about hurricanes is improving with good models of their behavior. But the experience in modifying that behavior is primitive so far. It is inherently difficult to find enough test cases, especially since experimentation on typhoons in the Western Pacific has been blocked for the time being by international political objections.

8. Although the Soviets and some U.S. private operators claim some success in suppressing hail by seeding clouds, our understanding of the physical processes that create hail is still weak. The one major U.S. field experiment increased our understanding of severe storms, but otherwise proved mostly the dimensions of what we do not yet know.

9. There have been many efforts to suppress lightning by seeding thunderstorms. Our knowledge of the processes involved is fair, but

the technology is still far from demonstrated, and the U.S. Forest Service has recently abandoned further lightning experiments.²

Lewis O. Grant recently summarized the state of general disagreement on the status of weather modification technology and its readiness for application.

There is a wide diversity of opinion on weather modification. Some believe that weather modification is now ready for widespread application. In strong contrast, others hold that application of the technology may never be possible or practical on any substantial scale.³

He concludes that—

Important and steady advances have been made in developing technology for applied weather modification, but complexity of the problems and lack of adequate research resources and commitment retard progress.⁴

In 1975, David Atlas, then president of the American Meteorological Society, expressed the following pessimistic opinion on the status of weather modification technology:

Almost no one doubts the economic and social importance of rainfall augmentation, hail suppression, fog dissipation, and severe storm abatement. But great controversy continues about just what beneficial modification effects have been demonstrated or are possible. Claims and counterclaims abound. After three decades of intense research and operational weather modification activities, only a handful of experiments have demonstrated beneficial effects to the general satisfaction of the scientific community.

To describe weather modification as a "technology" is to encourage misunderstanding of the state of the weather modification art. The word "technology" implies that the major substantive scientific foundations of the field have been established and, therefore, that all that is required is to develop and apply techniques. But one of the conclusions of the special AMS study on cloud physics was that "the major bottleneck impeding developments of useful deliberate weather modification techniques is the lack of an adequate scientific base."⁵

At a 1975 workshop on the present and future role of weather modification in agriculture, a panel of 10 meteorologists assessed the capabilities for modifying various weather and weather-related phenomena, both for the present and for the period 10 to 20 years in the future. Conclusions from this assessment are summarized in table 1. The table shows estimated capabilities for both enhancement and dissipation, and includes percentages of change and areas affected, where appropriate.⁶

A recent study by Barbara Farhar and Jack Clark surveyed the opinions of 551 scientists, all involved in some aspect of weather modification, on the current status of various weather modification technol-

² Weather Modification Advisory Board, "A U.S. Policy to Enhance the Atmospheric Environment," Oct. 21, 1977. In testimony by Harlan Cleveland. "Weather Modification," hearing before the Subcommittee on the Environment and the Atmosphere, Committee on Science and Technology, U.S. House of Representatives, 95th Cong., 1st sess., Oct. 26, 1977, Washington, D.C., U.S. Government Printing Office, 1977, pp. 28-30.

³ Grant, Lewis O., "Scientific and Other Uncertainties of Weather Modification." In William A. Thomas (editor), "Legal and Scientific Uncertainties of Weather Modification." Proceedings of a symposium convened at Duke University, Mar. 11-12, 1976, by the National Conference of Lawyers and Scientists. Durham, N.C., Duke University Press, 1977, p. 7.

⁴ *Ibid.*, p. 17.

⁵ Atlas, David, "Selling Atmospheric Science. The President's Page," Bulletin of the American Meteorological Society, vol. 56, No. 7, July 1975, p. 688.

⁶ Grant, Lewis O. and John D. Reid (compilers), "Workshop for an Assessment of the Present and Potential Role of Weather Modification in Agricultural Production." Colorado State University, Fort Collins, Colo., July 15-18, 1975, August 1975. PB-245-633, pp. 34-44.

ogies.⁷ Table 2 is a summary of the assessments of the level of development for each of 12 such technologies included in the questionnaire to which the scientists responded, and table 3 shows the estimates of effectiveness for 7 technologies where such estimates are pertinent. Results of this study were stratified in accordance with respondents' affiliation, specific education, level of education, age, and responsibility or interest in weather modification, and tabulated summaries of opinions on weather modification in accordance with these variables appear in the report by Farhar and Clark.⁸

TABLE 1.—ASSESSMENT OF THE CAPABILITIES FOR MODIFYING VARIOUS WEATHER AND WEATHER-RELATED NATURAL PHENOMENA, BASED ON THE OPINIONS OF 10 METEOROLOGISTS

[From Grant and Reid, 1975]

Modified variable	Enhancement				Dissipation			
	Now	10 to 20 yr	Amount change (per-cent)	Area (square miles)	Now	10 to 20 yr	Amount change (per-cent)	Area (square miles)
I. Clouds:								
1. Cold stratus.....	No (8)	Yes (7)	-----	1-1000	Yes (10)	Yes (10)	-----	1-1000
2. Warm stratus.....	No (10)	No (5)	-----	-----	No (8)	Yes (9)	-----	-----
3. Fog, cold.....	Yes (10)	Yes (10)	-----	1-10	Yes (10)	Yes (10)	-----	1-1000
4. Fog, warm.....	Yes (10)	Yes (10)	-----	1-100	Yes (10)	Yes (10)	-----	.1-1
5. Fog, artificial (for temperature control).....	Yes (10)	Yes (10)	-----	1-10	N/A	N/A	-----	-----
6. Contrails.....	Yes (10)	Yes (10)	-----	100-1000	No (10)	No (10)	-----	-----
7. Cirrus.....	Yes (5)	Yes (10)	-----	100-1000	No (10)	No (8)	-----	-----
8. Carbon black.....	No (10)	No (6)	-----	-----	N/A	N/A	-----	-----
9. Aerosol.....	Yes (7)	Yes (10)	-----	-----	N/A	N/A	-----	-----
II. Convective precipitation:								
1. Isolated small.....	Yes (7)	Yes (10)	100	10-100	Yes (5)	Yes (8)	100	10-100
2. Isolated large.....	No (6)	Yes (7)	15	100-1000	Yes (5)	Yes (8)	15	10-1000
3. Squall lines.....	Yes (5)	Yes (5)	20	100-10,000	No (8)	Yes (5)	20	100-10,000
4. Nocturnal.....	Yes (5)	Yes (6)	100	100-1000	No (8)	Yes (5)	100	100-1000
5. Imbedded cyclonic.....	Yes (9)	Yes (10)	30	300-6000	Yes (8)	Yes (10)	<5	300-6000
6. Imbedded Oro-graphic.....	Yes (9)	Yes (10)	20	300-6000	Yes (8)	Yes (10)	20	300-6000
III. Stratiform precipitation:								
1. Orographic.....	Yes (10)	Yes (10)	10	100-3000	Yes (10)	Yes (10)	10	100-3000
2. Cyclonic.....	No (10)	No (6)	-----	-----	No (10)	No (6)	-----	-----
3. Cloud water collection.....	Yes (10)	Yes (10)	-----	-----	N/A	N/A	-----	-----
IV. Hazards:								
1. Hail.....	Yes (5)	Yes (7)	(1)	100-60,000	Yes	Yes	30	100-60,000
2. Lightning.....	Yes (7)	Yes (9)	(1)	40,000	Yes (7)	Yes (9)	40	40,000
3. Erosion—wind gradient.....	No (10)	No (10)	-----	-----	No (10)	No (10)	-----	-----
4. Erosion—water drop size.....	Yes (5)	Yes (7)	(1)	10,000	Yes (5)	Yes (7)	-----	10,000
5. Wind—hurricane.....	No (5)	Yes (6)	-----	-----	No (6)	Yes (6)	-----	-----
6. Tornado.....	No (10)	Yes (5)	-----	-----	No (10)	Yes (5)	-----	-----
7. Blowdown.....	No (5)	Yes (5)	-----	-----	No (9)	Yes (5)	-----	-----
8. Floods—symoptic.....	No (10)	No (10)	-----	-----	No (10)	No (3)	-----	-----
9. Floods—mesoscale.....	No (9)	Yes (6)	-----	-----	No (9)	Yes (6)	-----	-----
10. Drought.....	No (10)	No (10)	-----	-----	Yes (5)	Yes (6)	-----	-----
V. Other:								
1. Albedo.....	Yes (5)	Yes (10)	-----	-----	Yes (5)	Yes (10)	-----	-----
2. Surface roughness.....	No (6)	Yes (6)	-----	-----	No (6)	Yes (6)	-----	-----
3. Topography changes.....	No (6)	Yes (5)	-----	-----	No (6)	Yes (5)	-----	10-100

¹ Uncertain.

⁷ Farhar, Barbara C. and Jack A. Clark, "Can We Modify the Weather? a Survey of Scientists." Final report, vol. 3 (draft), Institute of Behavioral Science, University of Colorado, Boulder, Colo., January 1978. (Based on research supported by the National Science Foundation under grants No. ENV74-18613 A03, GI-35452, GI-44087, and ERT74-18613, as part of "A Comparative Analysis of Public Support of and Resistance to Weather Modification Projects.") 89 pp.

⁸ Ibid.

TABLE 2.—ASSESSMENT OF THE LEVEL OF DEVELOPMENT OF TWELVE WEATHER MODIFICATION TECHNOLOGIES
BASED UPON A SURVEY OF 551 WEATHER MODIFICATION SCIENTISTS

[From Farhar and Clark, 1978]

Weather modification technology	Operations ¹		Research ²		Neither		Don't know		Other		Total No.
	Per-cent	No.	Per-cent	No.	Per-cent	No.	Per-cent	No.	Per-cent	No.	
Cold fog dispersal.....	78	406	8	42	0	1	14	72	0	0	521
Precipitation enhancement, winter orographic, continental.....	68	357	20	104	1	6	11	57	0	1	525
Precipitation enhancement, winter orographic, maritime.....	64	337	22	113	1	5	13	70	0	1	526
Hail suppression.....	46	244	49	256	1	4	4	23	0	1	528
Precipitation enhancement, summer convective, continental.....	43	227	49	258	2	10	6	31	0	1	527
Precipitation enhancement, summer convective, maritime.....	42	220	46	244	1	5	11	56	0	2	529
Warm fog dispersal.....	33	170	48	253	1	3	18	92	0	0	518
Precipitation enhancement with hail suppression.....	30	156	56	288	2	12	12	62	0	1	519
Precipitation enhancement, general storms.....	25	128	58	300	5	28	12	64	0	2	522
Lightning suppression.....	8	42	65	332	4	22	23	119	0	0	515
Hurricane suppression.....	4	19	75	388	4	23	17	88	0	2	520
Severe storm mitigation.....	3	13	68	353	9	47	20	101	0	1	515

¹ This category is a combination of two responses: "The technology is ready for operational application" and "The technology can be effectively applied; research should continue."

² This category is a combination of two responses: "The technology is ready for field research only" and "The technology should remain at the level of laboratory research."

TABLE 3.—ESTIMATES OF EFFECTIVENESS FOR SEVEN WEATHER MODIFICATION TECHNOLOGIES, BASED ON A SURVEY OF 551 WEATHER MODIFICATION SCIENTISTS
[From Farhat and Clark, 1978]

Technology	Number responding	Percent don't know	Percent giving estimates	Percent zero	Range of estimates ¹ (percent)	Median of estimates (percent)	Modal response, estimates ² (percent)	Mean estimates (percent)	Standard deviation of estimates (percent)
Hail suppression (reduction in crop damage over a year)-----	534	59.6	40.1	4.9	0 to 82		25 D.K., 50	30.0	9.7
Rainfall increase (continental convective, over a growing season, individual clouds)-----	504	45.0	54.4	3.57	0 to 300		20 D.K., 10	41.0	49.4
Rainfall increase (continental convective, over a growing season, area wide)-----	517	47.6	51.8	7.93	0 to 100		9 D.K., 10	10.5	10.9
Rainfall increase (maritime, over a year, individual clouds)-----	510	57.1	42.4	3.33	0 to 900		26 D.K., 100	63.2	98.5
Rainfall increase (maritime, over a year, area wide)-----	505	61.8	37.8	5.54	0 to 250		9 D.K., 10	15.1	27.1
Snowpack increase (orographic, winter season)-----	534	32.0	63.3	1.31	0 to 100		15 D.K., 15	18.3	16.5
Precipitation effects (tropical storms, coastal areas)-----	532	84.8	15.0	3.6					
Increases-----			7.5		0 to 159		19 D.K., 9	28.2	38.0
Decreases-----			2.1		0 to 69		12 D.K., 19	16.8	16.4
Increases and decreases-----			32.1						

¹ The value of zero was included in all computations of central tendency and distribution.

² Estimates of effectiveness are bimodal, one mode being "Don't know" (D.K.), the other numerical increases in precipitation for coastal areas from seeding tropical storms.

CLASSIFICATION OF WEATHER MODIFICATION TECHNOLOGIES

In a previous review of weather modification for the Congress, three possible classifications of activities were identified—these classifications were in accordance with (1) the nature of the atmospheric processes to be modified, (2) the agent or mechanism used to trigger or bring about the modification, or (3) the scale or dimensions of the region in which the modification is attempted.⁹ The third classification was chosen in that study, where the three scales considered were the microscale (horizontal distances, generally less than 15 kilometers), the mesoscale (horizontal distances generally between 15 and 200 kilometers), and the macroscale (horizontal distances generally greater than 200 kilometers).¹⁰ Examples of modification of processes on each of these three scales are listed in table 4, data in which are from Hartman.¹¹ Activities listed in the table are illustrative only, and there is no intent to indicate that these technologies have been developed, or even attempted in the case of the listed macroscale processes.

TABLE 4.—WEATHER AND CLIMATE MODIFICATION ACTIVITIES CLASSIFIED ACCORDING TO THE SCALE OR DIMENSIONS OF THE REGION IN WHICH THE MODIFICATION IS ATTEMPTED

[Information from Hartman, 1966]

Scale	Horizontal dimensions	Examples of modification processes
Microscale.....	Less than 15 km.....	Modification of human microclimates. Modification of plant microclimates. Evaporation suppression. Fog dissipation. Cloud dissipation. Hail prevention. Precipitation through individual cloud modification.
Mesoscale.....	15 to 200 km.....	Precipitation from cloud systems. Hurricane modification. Horization of tornado systems.
Macroscale.....	Greater than 200 km.....	Changes to global atmospheric circulation patterns. Melting the Arctic icecap. Diverting ocean currents.

In this chapter the characteristics and status of weather modification activities will be classified and discussed according to the nature of the processes to be modified. This seems appropriate since such a breakdown is more consonant with the manner the subject has been popularly discussed and debated, and it is consistent with the directions in which various operational and research activities have moved. Classification by the second criterion above, that is, by triggering agent or mechanism, focuses on technical details of weather modification, not of chief interest to the public or the policymaker, although these details will be noted from time to time in connection with discussion of the various weather modification activities.

In the following major section, then, discussion of the principles and the status of planned weather modification will be divided accord-

⁹ Hartman, Lawton M. "Characteristics and Scope of Weather Modification." In U.S. Congress, Senate Committee on Commerce. "Weather Modification and Control," Washington, D.C., U.S. Government Printing Office, 1966. (89th Cong., 2d sess., Senate Rept. No. 1139, prepared by the Legislative Reference Service, Library of Congress), p. 20.

¹⁰ Ibid.

¹¹ Ibid., pp. 21-31.

ing to the major broad categories of phenomena to be modified; these will include:

- Precipitation augmentation.
- Hail suppression.
- Fog dissipation.
- Lightning suppression.
- Severe storm mitigation.

In subsequent major sections of this chapter there are reviews of some of the specific technical problem areas common to most weather modification activities and a summary of recommended research activities.

In addition to the intentional changes to atmospheric phenomena discussed in this chapter, it is clear that weather and climate have also been modified inadvertently as the result of man's activities and that modification can also be brought about through a number of naturally occurring processes. These unintentional aspects of weather and climate modification will be addressed in the following chapter of this report.¹²

PRINCIPLES AND STATUS OF WEATHER MODIFICATION TECHNOLOGIES

Before discussing the status and technologies for modification of precipitation, hail, fog, lightning, and hurricanes, it may be useful to consider briefly the basic concepts of cloud modification. The two major principles involved are (1) colloidal instability and (2) dynamic effects. Stanley Changnon describes how each of these principles can be effective in bringing about desired changes to the atmosphere:¹³

Altering colloidal stability.—The physical basis for most weather modification operations has been the belief that seeding with certain elements would produce colloidal instability in clouds, either prematurely, to a greater degree, or with greater efficiency than in nature. Most cloud seeding presumes that at least a portion of the treated cloud is supercooled, that nature is not producing any or enough ice at that temperature of the cloud, and that treatment with chemical agents of refrigerants will change a proportion of the cloud to ice. The resultant mixture of water and ice is unstable and there is a rapid deposition of water vapor upon the ice and a simultaneous evaporation of water from the supercooled droplets in the cold part of the cloud. The ice crystals so formed become sufficiently large to fall relative to remaining droplets, and growth by collection enhances the probability that particles of ice or water will grow to be large enough to fall from the cloud and become precipitation.

This process of precipitation enhancement using ice nucleants has been demonstrated for the stratiform type cloud, and generally for those which are orographically-produced and supercooled. Cumulus clouds in a few regions of the United States have also been examined for the potential of colloidal instability in their supercooled portions. This has been founded on beliefs that precipitation (1) can be initiated earlier than by natural causes, or (2) can be produced from a cloud which was too small to produce precipitation naturally.

Seeding in the warm portion of the cloud, or in "warm clouds" (below the freezing level), has also been attempted so as to alter their colloidal instability. Warm-cloud seeding has primarily attempted to provide the large droplets necessary to initiate the coalescence mechanism, and is of value in clouds where insufficient large drops exist. In general alteration of the coalescence process primarily precipitates out the liquid water naturally present in a cloud, whereas the ice-crystal seeding process also causes a release of latent energy that conceivably results in an intensification of the storm, greater cloud growth, and additional precipitation.

Altering cloud dynamics.—The effects to alter the colloidal instability of clouds, or their microphysical processes, have been based on the concept of rain

¹² See p. 145.

¹³ Changnon, Stanley A., Jr. "Present and Future of Weather Modification: Regional Issues." *The Journal of Weather Modification*, vol. 7, No. 1, April 1975, pp. 154-156.

increase through increasing the precipitation efficiency of the cloud. Simpson and Dennis (1972) showed that alterations of cloud size and duration by "dynamic modification" could produce much more total rainfall than just altering the precipitation efficiency of the single cloud. In relation to cumulus clouds, "dynamic seeding" simply represents alteration one step beyond that sought in the principle of changing the colloidal stability. In most dynamic seeding efforts, the same agents are introduced into the storm but often with a greater concentration, and in the conversion of water to ice, enormous amounts of latent heat are hopefully released producing a more vigorous cloud which will attain a greater height with accompanying stronger updrafts, a longer life, and more precipitation. Seeding to produce dynamic effects in cloud growth, whether stratiform or cumuliform types, is relatively recent at least in its serious investigation, but it may become the most important technique. If through controlled cloud seeding additional uplift can be produced, the productivity in terms of rainfall will be higher whether the actual precipitation mechanism involved is natural or artificial.

It has been proposed that the selective seeding of cumulus clouds also can either (a) bring upon a merger of two or more adjacent clouds and a much greater rainfall production through a longer-lived, larger cloud * * * or (b) produce eventually an organized line of clouds (through selective seeding of randomized cumulus). The latter could allegedly be accomplished by minimizing and organizing the energy into a few vigorous systems rather than a larger number of isolated clouds.

Essentially, then, dynamic seeding is a label addressed to processes involved in altering cloud microphysics in a selective and preferential way to bring upon more rainfall through an alteration of the dynamical properties of the cloud system leading to the development of stronger clouds and mesoscale systems. Actually, dynamic effects might be produced in other ways such as alterations of the surface characteristics to release heat, by the insertion of chemical materials into dry layers of the atmosphere to form clouds, or by redistribution of precipitation through microphysical interactions in cloud processes.

The various seeding materials that have been used for cloud modification are intended, at least initially, to change the microphysical cloud structure. Minute amounts of these materials are used with the hope that selected concentrations delivered to specific portions of the cloud will trigger the desired modifications, through a series of rapid multiplicative reactions. Seeding materials most often used are classified as (1) ice nuclei, intended to enhance nucleation in the supercooled part of the cloud, or (2) hygroscopic materials, designed to alter the coalescence process.¹⁴

Glaciation of the supercooled portions of clouds has been induced by seeding with various materials. Dry ice injected into the subfreezing part of a cloud or of a supercooled fog produces enormous numbers of ice crystals. Artificial ice nuclei, with a crystal structure closely resembling that of ice, usually silver iodide smoke particles, can also produce glaciation in clouds and supercooled fogs. The organic fertilizer, urea, can also induce artificial glaciation, even at temperatures slightly warmer than freezing. Urea might also enhance coalescence in warm clouds and warm fogs. Water spray and fine particles of sodium chloride have also been used in hygroscopic seeding, intended to alter the coalescence process. There have been attempts to produce coalescence in clouds or fog using artificial electrification, either with chemicals that increase droplet combination by electrical forces, or with surface arrays of charged wires whose discharges produce ions which, attached to dust particles, may be transported to the clouds.¹⁵

Problems of cloud seeding technology and details of seeding delivery methods are discussed in a later section of this chapter, as are

¹⁴ Ibid., p. 156.

¹⁵ Ibid., pp. 156-157.

some proposed techniques for atmospheric modification that go beyond cloud seeding.¹⁶

PRECIPITATION AUGMENTATION

The seeding of clouds to increase precipitation, either rainfall or snowfall, is the best known and the most actively pursued weather modification activity. Changes in clouds and precipitation in the vicinity of cloud seeding operations have shown unquestionably that it is possible to modify precipitation. There is evidence, however, that such modification attempts do not always increase precipitation, but that under some conditions precipitation may actually be decreased, or at best no net change may be effected over an area. Nevertheless, continued observations of clouds and precipitation, from both seeded and nonseeded regions and from both experiments and commercial operations, are beginning to provide valuable information which will be useful for distinguishing those conditions for which seeding increases, decreases, or has no apparent effect on precipitation. These uncertainties were summarized in one of the conclusions in a recent study on weather modification by the National Academy of Sciences:¹⁷

The Panel now concludes on the basis of statistical analysis of well-designed field experiments that ice-nuclei seeding can sometimes lead to more precipitation, can sometimes lead to less precipitation, and at other times the nuclei have no effect, depending on the meteorological conditions. Recent evidence has suggested that it is possible to specify those microphysical and mesophysical properties of some cloud systems that determine their behavior following artificial nucleation.

Precipitation enhancement has been attempted mostly for two general types of cloud forms, both of which naturally provide precipitation under somewhat different conditions. Convective or cumulus clouds are those which are formed by rising, unstable air, brought about by heating from below or cooling in the upper layers. Under natural conditions cumulus clouds may develop into cumulo-nimbus or "thunderheads," capable of producing heavy precipitation. Cumulus clouds and convective systems produce a significant portion of the rain in the United States, especially during critical growing seasons. Attempts to augment this rainfall from cumulus clouds under a variety of conditions have been underway for some years with generally uncertain success. The other type of precipitation-producing clouds of interest to weather modifiers are the orographic clouds, those which are formed when horizontally moving moisture-laden air is forced to rise over a mountain. As a result of the cooling as the air rises, clouds form and precipitation often falls on the windward side of the mountain. Through seeding operations, there have been attempts to augment precipitation through acceleration of this process, particularly in winter, in order to increase mountain snowpack.

Figures 1 and 2 show regions of the coterminous United States which are conducive to precipitation management through seeding of spring and summer convective clouds and through seeding orographic cloud systems, respectively. The principles of precipitation

¹⁶ See pp. 115 and 129.

¹⁷ National Academy of Sciences, National Research Council, Committee on Atmospheric Sciences, "Weather and Climate Modification: Problems and Progress," Washington, D.C., 1973, p. 4.

enhancement for both cumulus and orographic clouds, and the present state of knowledge and technology for such modification, are discussed in the following sections.

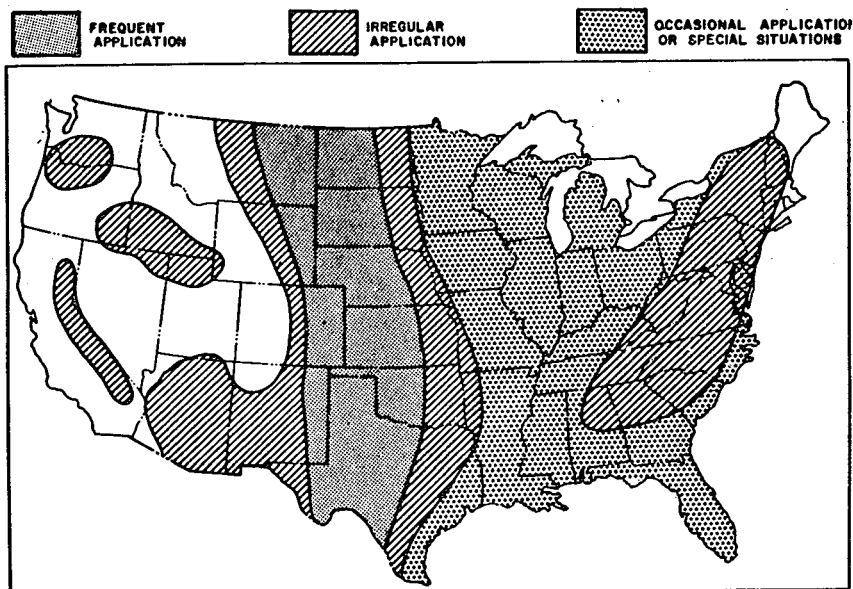


FIGURE 1.—Regions where precipitation management may be applied to enhance rainfall from spring and summer showers.

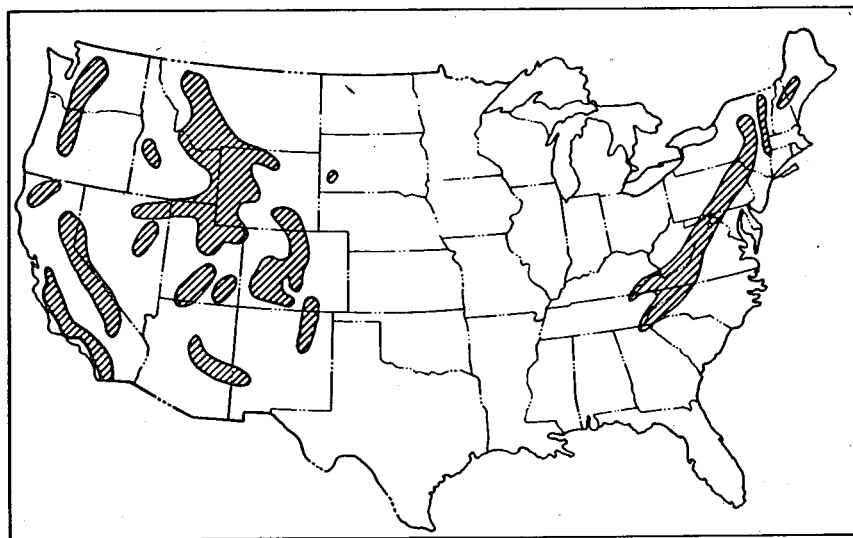


FIGURE 2.—Regions where precipitation management may be applied to enhance snowfall from winter orographic weather systems, thus augmenting spring and summer runoff from mountain snowpacks.

Cumulus clouds

If air containing moisture is cooled sufficiently and if condensation nuclei such as dust particles are present, precipitation may be produced. This process occurs when air is forced to rise by convection, so that the water vapor condenses into clouds. Cumulus clouds are the woolly vertical clouds with a flat base and somewhat rounded top, whose origin can always be traced to the convection process. They can most often be observed during the summer and in latitudes of high temperature. When updrafts become strong under the proper conditions, cumulus clouds often develop into cumulonimbus clouds, the principal producer of precipitation. About three-fourths of the rain in the tropics and subtropics and a significant portion of that falling on the United States is provided from cumulus clouds and convective systems.

The science of cloud study, begun in the 1930's and greatly expanded following World War II, includes two principal aspects—cloud microphysics and cloud dynamics. Though once approached separately by different groups of scientists, these studies are now merging into a single discipline. In cloud physics or microphysics the cloud particles—such as condensation and freezing nuclei, water droplets, and ice crystals—are studied along with their origin, growth, and behavior. Cloud dynamics is concerned with forces and motions in clouds, the prediction of cloud structure, and the life cycle of updrafts and downdrafts.¹⁸

For cloud modification purposes, present theories of microphysical processes provide an ample basis for field seeding experiments; however, further work is still needed on laboratory experiments, improved instrumentation, and research on assumptions. On the other hand, the processes in cloud dynamics are not completely understood and require continued research.¹⁹

Most cumulus clouds evaporate before they have had opportunity to produce precipitation at the Earth's surface. In fact many clouds begin to dissipate at about the same time that rain emerges from their bases, leading to the impression that they are destroyed by the formation of precipitation within them. This phenomenon is not yet fully understood. Cumulus clouds have a life cycle; they are born, mature, and eventually age and die. Small cumuli of the trade regions live only about 5 to 10 minutes, while medium-sized ones exist for about 30 minutes. On the other hand, a giant cumulonimbus cloud in a hurricane or squall line may be active for one to several hours. In its lifetime it may exchange over 50 million tons of water, producing heavy rain, lightning, and possibly hail. At all times, however, a cumulus cloud struggles to exist; there is a precarious balance between the forces aiding its growth and its destruction.²⁰

The increasing capability to simulate cloud processes on the computer has been a major advance toward understanding cloud modification. The ways in which cloud microphysics influences convective

¹⁸ Simpson, Joanne and Arnett S. Dennis, "Cumulus Clouds and Their Modification." In Wilmot N. Hess (ed.), "Weather and Climate Modification," New York, John Wiley & Sons, 1974, p. 233.

¹⁹ Moschandreas, Demetrios J., and Irving Leichter, "Present Capabilities to Modify Cumulus Clouds," Geomet. Inc. report No. EF-463. Final report for U.S. Navy Environmental Prediction Research Facility, Mar. 30, 1976, p. 209.

²⁰ Simpson and Dennis, "Cumulus Clouds and Their Modification," 1947, pp. 234-235.

dynamics are not well documented or modeled, however. Feedback mechanisms are dynamic and thermodynamic. Dynamically, the buoyancy is reduced by the weight of the particles formed within the cloud, sometimes called "water loading." Modeling suggests that thermodynamic feedback from the microphysics can be even more important, as evaporation at the edges of the cloud produces cooling and thus induces downdrafts. Observations confirm this important influence of evaporation, particularly where the cloud environment is relatively dry, but the effect is minimized in humid tropical regions.²¹

Cumulus modification experiments

An enormous amount of energy is expended in natural atmospheric processes. As much energy as the fusion energy of a hydrogen super-bomb is released in a large thunderstorm, and in a moderate-strength hurricane the equivalent of the energy of 400 bombs is converted each day. In his attempt to modify precipitation from clouds, man must therefore look for some kind of a trigger mechanism by which such energetically charged activities can be controlled, since he cannot hope to provide even a fraction of the energy involved in the natural process. A major problem in evaluating modification efforts is the large natural variability in atmospheric phenomena. A cumulus cloud can, in fact, do almost anything all by itself, without any attempt to modify its activity by man. This high variability has led the layman to overestimate grossly what has been and can be done in weather modification. In designing an experiment, this variability requires that there be sound statistical controls.²²

Precipitation is formed by somewhat different processes in warm clouds and in subfreezing clouds. In the former, droplets are formed from condensation of water vapor on condensation nuclei and grow through collision and coalescence into raindrops. In subfreezing clouds, such as the cumuli under discussion, supercooled water droplets are attached to ice nuclei which grow into larger ice particles. When large enough, these particles fall from the cloud as snow or sleet or may be converted to rain if the temperature between the cloud and the Earth's surface is sufficiently warm. Increasing precipitation through artificial means is more readily accomplished in the case of the subfreezing clouds. In addition, attempts have been made to promote the merging of cumulus clouds in order to develop larger cloud systems which are capable of producing significantly more precipitation than would be yielded by the individual small clouds.

Nearly all cumulus experiments have involved "seeding" the clouds with some kind of small particles. Sometimes the particles are dispersed from the ground, using air currents to move them into the clouds. Most often the materials are dispensed from aircraft, by releasing them upwind of the target clouds, by dropping them into the cloud top, by using the updraft from beneath the cloud, or by flying through the cloud. Although more expensive, aircraft seeding permits more accurate targeting and opportunity for measurements and observations. In the Soviet Union, cumulus clouds have been seeded success-

²¹ Simpson, Joanne, "Precipitation Augmentation from Cumulus Clouds and Systems: Scientific and Technical Foundations," 1975, *Advances in Geophysics*, vol. 19, New York, Academic Press, 1976, pp. 10-11.

²² Simpson and Dennis, "Cumulus Clouds and Their Modification," 1974, pp. 240-241.

fully with artillery shells and rockets, using radar to locate parts of the clouds to be seeded.²³

Augmentation of precipitation in cumulus clouds has been attempted both by accelerating the coalescence process and by initiating ice particle growth in the presence of supercooled water. In fact, these processes are essentially identical in cumuli where the tops extend above the freezing level.

Prior to the 1960's nearly all supercooled seeding experiments and operations were concerned with attempting to increase precipitation efficiency, based on consideration of cloud microstructure.²⁴ This is essentially a static approach, intended to produce precipitation by increasing the total number of condensation nuclei, through the introduction of artificial nuclei injected by seeding into or under the clouds. This approach has been moderately successful in convective storms with conducive cloud microstructure in a number of locations—California, Israel, Switzerland, and Australia—where clouds are often composed of small supercooled droplets, typical of winter convection and of continental air masses.²⁵ On the other hand, the large cumulus clouds originating in tropical and subtropical ocean regions, which are evident over much of the eastern United States during the summer, are much less influenced by this static approach. A technique known as dynamic seeding has shown promise in enhancing precipitation from clouds of this type.

According to dynamic seeding philosophy, the strength, size, and duration of vertical currents within the cloud have stronger control on cumulus precipitation than does the microstructure. In this technique, first demonstrated in the 1960's, the seeding provides artificial nuclei around which supercooled water freezes, liberating large quantities of latent heat of fusion, within the clouds, causing them to become more buoyant and thus to grow to greater heights. This growth invigorates circulation within the cloud, causes increased convergence at its base, fosters more efficient processing of available moisture, and enhances rainfall through processes by which cumuli ordinarily produce such precipitation. Results of the Florida Area Cumulus Experiment (FACE), conducted by the U.S. Department of Commerce, seem to indicate that dynamic seeding has been effective in increasing the sizes and lifetimes of individual cumuli and the localized rainfall resulting from them.²⁶

Success thus far in rain enhancement from dynamic seeding of cumulus has been demonstrated through seeding techniques applied to single, isolated clouds. In addition to the experiments in Florida, dynamic seeding of single clouds has been attempted in South Dakota, Pennsylvania, Arizona, Australia, and Africa, with results similar to those obtained in Florida.²⁷ It appears, however, that a natural process necessary for heavy and extensive convective rainfall is the merger of cloud groups. Thus, this process of cloud merger must be promoted in order for cloud seeding to be effective in augmenting rainfall from

²³ *Ibid.*, p. 242.

²⁴ *Ibid.*, 1974, pp. 246–247.

²⁵ *Ibid.*, p. 247.

²⁶ William L. Woodley, Joanne Simpson, Ronald Blondini, and Joyce Berkeley. "Rainfall Results, 1970–1975; Florida Area Cumulus Experiment," *Science*, vol. 195, No. 4280, Feb. 25, 1977, p. 735.

²⁷ Simpson and Dennis, "Cumulus Clouds and Their Modification." 1974, p. 261.

cumulus clouds. The FACE experiment has been designed to investigate whether dynamic seeding can induce such cloud merger and increased rainfall.²⁸ Area wide cumulus cloud seeding experiments are also planned for the U.S. Department of the Interior's High Plains Cooperative program (HIPLEX), being conducted in the Great Plains region of the United States.^{29, 30} There has been some indication that desired merging has been accomplished in the Florida experiment.³¹ Though this merging and other desirable effects may be achieved for Florida cumulus, it must be established that such mergers can also be induced for other convective systems which are found over most of the United States east of the Great Plains. Changnon notes that, "The techniques having the most promise for rain enhancement from convective clouds have been developed for single, isolated types of convective clouds. The techniques have been explored largely through experimentation with isolated mountain-type storms or with isolated semitropical storms. * * * Weather modification techniques do not exist for enhancing precipitation from the multicellular convective storms that produce 60 to 90 percent of the warm season rainfall in the eastern two-thirds of the United States."³²

Effectiveness of precipitation enhancement research and operations

A major problem in any precipitation enhancement project is the assessment of whether observed increases following seeding result from such seeding or occur as part of the fluctuations in natural precipitation not related to the seeding. This evaluation can be attempted through observations of physical changes in the cloud system which has been seeded and through statistical studies.

Physical evaluation requires theoretical and experimental investigations of the dispersal of the seeding agent, the manner that seeding has produced changes in cloud microstructure, and changes in gross characteristics of a cloud or cloud system. Our understanding of the precipitation process is not sufficient to allow us to predict the magnitude, location, and time of the start of precipitation. Hence, because of this lack of detailed understanding and the high natural variability of precipitation, it is necessary to use statistical methods as well. There is a closer physical link between seeding and observable changes in cloud microstructure; however, even the latter can vary widely with time and position in natural, unseeded clouds, so that statistical evaluation is also required with regard to the measurement of these quantities.³³

It should first be determined whether the seeding agent reached the intended region in the cloud with the desired concentration rather

²⁸ Woodley, et al., "Rainfall Results, 1970-1975; Florida Area Cumulus Experiment," 1977, p. 735.

²⁹ Bureau of Reclamation, U.S. Department of the Interior, "High Plains Cooperative Program: Progress and Planning Report No. 2," Denver, March 1976, p. 5.

³⁰ The history, purposes, organization, and participants in the FACE and HIPLEX programs are discussed along with other programs of Federal agencies in chapter 5 of this report.

³¹ William L. Woodley and Robert I. Sax, "The Florida Area Cumulus Experiment: Rationale, Design, Procedures, Results, and Future Course," U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, NOAA technical report ERL 354-WMPO 6, Boulder, Colo., January 1976, pp. 41-45.

³² Changnon, Stanley A., Jr., "Present and Future of Weather Modification: Regional Issues" 1975, pp. 159-162.

³³ Warner, J., "The Detectability of the Effects of Seeding." In World Meteorological Organization. Weather Modification Programme, position papers used in the preparation of the plan for the Precipitation Enhancement Experiment (PEP), Precipitation Enhancement Project Report No. 2. Geneva, November 1976, annex I, p. 43.

than spreading into other areas selected as controls. When the agent has been delivered by aircraft, this problem is usually minimized, though even in this case, it is desirable to learn how the material has diffused through the cloud. When ground-based seeding generators are used, the diffusion of the material should be studied both by theoretical studies and by field measurements. Such measurements may be made on the seeding agent itself or on some trace material released either with the seeding agent or separately; this latter might be either a fluorescent material such as zinc sulphide or any of various radioactive materials. Sometimes the tracer might be tracked in the cloud itself, while in other experiments it may be sufficient to track it in the precipitation at the surface.³⁴

In looking for cloud changes resulting from seeding, the natural cloud behavior is needed as a reference; however, since the characteristics of natural clouds vary so widely, it is necessary to observe a number of different aspects of the properties and behavior of seeded clouds against similar studies of unseeded clouds in order to be able to differentiate between the two. It is further desirable to relate such behavior being studied to predictions from conceptual and numerical models, if possible. Direct observations should be augmented by radar studies, but such studies should substitute for the direct measurements only when the latter are not possible.³⁵

A statistical evaluation is usually a study of the magnitude of the precipitation in the seeded target area in terms of its departure from the expected value. The expected quantity can either be determined from past precipitation records or through experimental controls. Such controls are established by dividing the experimental time available roughly in half into periods of seeding and nonseeding, on a random basis. The periods may be as short as a day or be 1 or 2 weeks in duration. The precipitation measured during the unseeded period is used as a measure of what might be expected in the seeded periods if seeding hadn't occurred. In another technique, control areas are selected where precipitation is highly correlated with that in the target area but which are never seeded. The target area is seeded on a random basis and its rainfall is compared with that of the control area for both seeded and unseeded periods. Another possibility includes the use of two areas, either of which may be chosen for seeding on a random basis. Comparisons are then made of the ratio of precipitation in the first area to that in the second with the first area seeded to the same ratio when the second is also seeded. There are many variations of these basic statistical designs, the particular one being used in a given experiment depending on the nature of the site and the measuring facilities available. As with the seeding techniques employed and the physical measurements which are made, experimental design can only be finalized after a site has been selected and its characteristics studied.³⁶

Results achieved through cumulus modification

Cumulus modification is one of the most challenging and controversial areas in weather modification. In some cases randomized seeding efforts in southern California and in Israel have produced significant

³⁴ Ibid., p. 44.

³⁵ Ibid.

³⁶ Ibid., p. 45.

precipitation from bands of winter cyclonic storms. However, attempts have been less promising in attributing increased rain during summer conditions to definitive experiments. There has been some success in isolated tropical cumuli, where seeding has produced an increase in cloud height and as much as a twofold to threefold increase in rainfall.³⁷

In the Florida area cumulus experiment (FACE), the effects on precipitation over a target area in southern Florida as a result of seeding cumuli moving over the area is being studied under the sponsorship of the National Oceanic and Atmospheric Administration (NOAA). Analysis of the data from 48 days of experimentation through 1975 provided no evidence that rainfall over the fixed target area of 13,000 square kilometers had been altered appreciably from dynamic seeding. On the other hand, there is positive evidence for increased precipitation from seeding for clouds moving through the area.³⁸

When FACE data from the 1976 season are combined with previous data, however, increasing the total number of experimental days to 75, analysis shows that dynamic seeding under appropriate atmospheric conditions was effective in increasing the growth and rain production of individual cumulus clouds, in inducing cloud merger, and in producing rainfall increases from groups of convective clouds as they pass through the target area. A net increase seemed to result from the seeding when rainfall on the total target area is averaged.³⁹

Further discussion of FACE purposes and results is found under the summary of weather modification programs of the Department of Commerce in chapter 5.⁴⁰

Recent advances in cumulus cloud modification

In the past few years some major advances have been achieved in cumulus experimentation and in improvement of scientific understanding. There has been progress in (1) numerical simulation of cumulus processes and patterning; (2) measurement techniques; (3) testing, tracing, delivery, and targeting of seeding materials; and (4) application of statistical tools. Recognition of the extreme difficulty of cumulus modification and the increased concept of an overall systems approach to cumulus experimentation have also been major advances.⁴¹

Orographic clouds and precipitation

In addition to the convection clouds, formed from surface heating, clouds can also be formed when moist air is lifted above mountains as it is forced to move horizontally. As a result, rain or snow may fall, and such precipitation is said to be orographic, or mountain induced. The precipitation results from the cooling within the cloud and charac-

³⁷ Sax, R. I., S. A. Changnon, L. O. Grant, W. F. Hirschfeld, P. V. Hobbs, A. M. Kahan, and J. Simpson, "Weather Modification: Where Are We Now and Where Should We Be Going? An Editorial Overview," *Journal of Applied Meteorology*, vol. 14, No. 5, August 1975, p. 662.

³⁸ Woodley, et al., "Rainfall Results, 1970-1975; Florida Area Cumulus Experiment," 1977, p. 742.

³⁹ Woodley, William L., Joanne Simpson, Ronald Biondini, and Jill Jordan, "NOAA's Florida Area Cumulus Experiment; Rainfall Results, 1970-1976." In preprints from the Sixth Conference on Planned and Inadvertent Weather Modification, Champaign, Ill., Oct. 10-13, 1977. Boston, American Meteorological Society, 1977, p. 209.

⁴⁰ See p. 292.

⁴¹ Sax, et. al. "Weather Modification: Where Are We Now and Where Should We Be Going? An Editorial Overview," 1975, p. 663.

teristically falls on the windward side of the mountain. As the air descends on the leeward side of the mountain, there is warming and dissipation of the clouds, so that the effect of the mountains is to produce a "rain shadow" or desert area. The Sierra Nevada in western North America provide such conditions for orographic rain and snow along the Pacific coast and a rain shadow east of the mountains when moisture laden air generally flows from the Pacific eastward across this range.

The western United States is a primary area with potential for precipitation augmentation from orographic clouds. This region receives much of its annual precipitation from orographic clouds during winter, and nearly all of the rivers start in the mountains, deriving their water from melting snowpacks. The major limitation on agriculture here is the water supply, so that additional water from increased precipitation is extremely valuable. Streamflow from melting snow is also important for the production of hydroelectric power, so that augmentation of precipitation during years of abnormally low natural snowfall could be valuable in maintaining required water levels necessary for operation of this power resource. Orographic clouds provide more than 90 percent of the annual runoff in many sections of the western United States.⁴²

Figure 3 (a) and (b) are satellite pictures showing the contrast between the snow cover over the Sierra Nevada on April 28, 1975, and on April 19, 1977. This is a graphical illustration of why much of California was drought stricken during 1977. The snowpack which customarily persists in the highest elevations of the Sierras until July had disappeared by mid-May in 1977.⁴³

The greatest potential for modification exists in the winter in this region, while requirements for water reach their peak in the summer; hence, water storage is critical. Fortunately, the snowpack provides a most effective storage, and in some places the snowmelt lasts until early July. Water from the snowmelt can be used directly for hydroelectric power generation or for irrigation in the more arid regions, while some can be stored in reservoirs for use during later months or in subsequent dry years. In some regions where the snowpack storage is not optimum, offseason orographic precipitation is still of great value, since the water holding capacity of the soil is never reached and additional moisture can be held in the soil for the following growing season.

Orographic clouds are formed as moist air is forced upward by underlying terrain. The air thus lifted, containing water vapor, cools and expands. If this lifting and cooling continue, the air parcels will frequently reach saturation. If the air becomes slightly supersaturated, small droplets begin to form by condensation, and a cloud develops, which seems to hang over the mountain peak. The location where this condensation occurs can be observed visually by the edge of the cloud on the windward side of the mountain. Upon descent in the lee of the mountain the temperature and vapor capacity of the air parcel again

⁴² Grant, Lewis O. and Archie M. Kahan, "Weather Modification for Augmenting Orographic Precipitation." In Wilmot N. Hess (editor), "Weather and Climate Modification," New York. Wiley, 1974. p. 285.

⁴³ U.S. Department of Commerce, news release, NOAA 77-234. NOAA Public Affairs Office, Rockville, Md., Aug. 17, 1977.

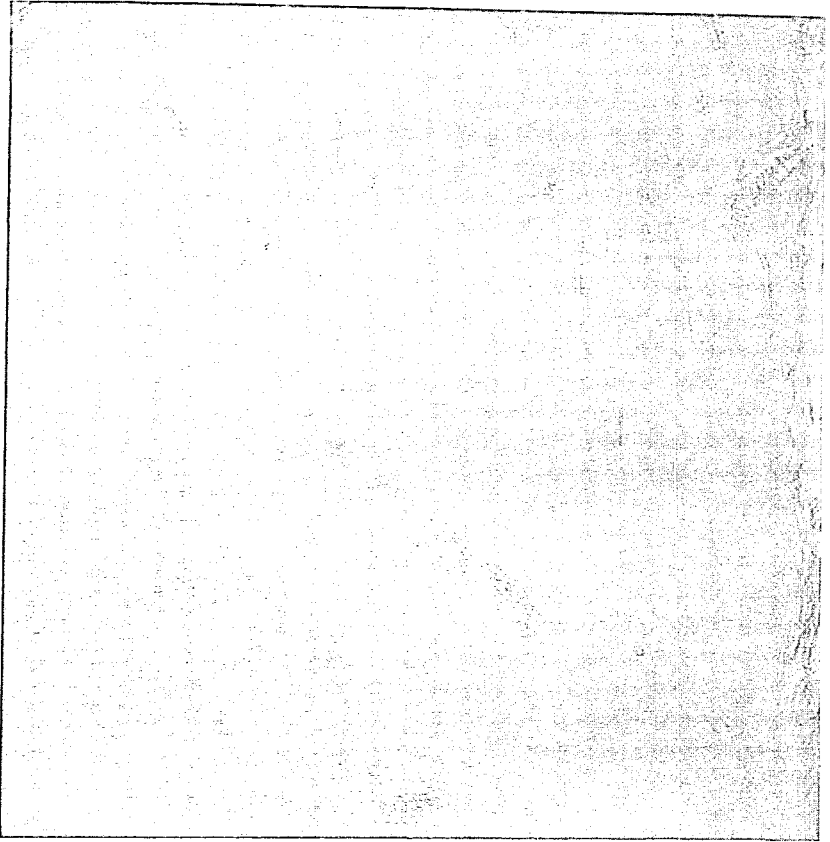
increase, so that any remaining liquid droplets or ice crystals evaporate.⁴⁴



(a) April 28, 1975

FIGURE 3.—NOAA-3 satellite pictures of the snowcover on the Sierra Nevada Mountains in (a) April 1975 and (b) April 1977. (Courtesy of the National Oceanic and Atmospheric Administration.)

⁴⁴ Sax. et al. "Weather Modification: Where Are We Now and Where Should We Be Going?" an editorial overview, 1975, pp. 657-658.



(b) April 19, 1977

The supercooled cloud droplets exist as liquid at temperatures down to about -20°C ; but at temperatures colder than -20°C , small ice crystals begin to form around nuclei that are naturally present in the atmosphere. Once formed, the ice crystals grow rapidly because the saturation vapor pressure over ice is less than that over water. As the crystals increase they may fall and eventually may reach the ground as snow. The temperature at the top of the cloud is an important factor in winter storms over mountains, since natural ice crystals will not form in large quantities if the cloud top is warmer than -20°C . If the temperature is below -20°C , however, a large fraction of the cloud particles will fall as snow from natural processes.⁴⁵

⁴⁵ Weisbecker, Leo W. (compiler), "The Impacts of Snow Enhancement: Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado River Basin," Norman, Okla., University of Oklahoma Press, 1974, pp. 64-66.

Orographic precipitation modification

According to Grant and Kahan, " * * * research has shown that orographic clouds * * * provide one of the most productive and manageable sources for beneficial weather modification."⁴⁶ In a recent study by the National Academy of Sciences, it was concluded broadly that orographic clouds provide one of the "main possibilities of precipitation augmentation," based on the considerations below:⁴⁷

A supply of cloud water that is not naturally converted into precipitation sometimes exists for extended periods of time;

Efficient seeding agents and devices are available for treating these clouds;

Seeding agents can sometimes (not always) be delivered to the proper cloud location in proper concentrations and at the proper time;

Microphysical cloud changes of the type expected and necessary for seeding have been demonstrated;

Substantial increases in precipitation with high statistical significance have been achieved in some well-designed randomized experiments for clouds that, based on physical concepts, should have seeding potential; and

Augmentation of orographic precipitation can have great economic potential.

Although natural ice crystals will not form in sufficient numbers if the cloud top is warmer than -20°C , it has been shown that particles of silver iodide smoke will behave as ice nuclei at temperatures somewhat warmer than -20°C , so that ice crystals can be produced by such artificial nuclei in clouds with temperatures in the range of -10° to -20°C . Whereas in the natural state, with few active nuclei at these temperatures, the cloud particles tend to remain as water droplets, introduction of the silver iodide can quickly convert the supercooled cloud into ice crystals. Then, the natural growth processes allow the crystals to grow to sufficient size for precipitation as snow.⁴⁸

Meteorological factors which favor increased snowfall from orographic clouds through cloud seeding are summarized by Weisbecker:⁴⁹

The component of the airflow perpendicular to the mountain ridge must be relatively strong.

The air must have a high moisture content. Generally, high moisture is associated with above-normal temperatures.

The cloud, including its upper boundary, should be at a temperature warmer than -20°C . Since temperature decreases with increasing altitude, this temperature criterion limits the altitude of the cloud top. However, it is advantageous for the cloud base to be low, since the water droplet content of the cloud will then be relatively large.

⁴⁶ Grant and Kahan, "Weather Modification for Augmenting Orographic Precipitation," 1974, p. 282.

⁴⁷ Committee on Climate and Weather Fluctuations and Agricultural Production, National Research Council, "Climate and Food: Climatic Fluctuation and U.S. Agricultural Production," National Academy of Sciences, Washington, D.C., 1976, p. 136.

⁴⁸ Weisbecker, "The Impacts of Snow Enhancement; Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado Basin," 1974, p. 66.

⁴⁹ Ibid. pp. 66-67.

It must be possible to disperse silver iodide particles within the cloud in appropriate numbers to serve as ice crystal nuclei. If ground generators are used, the silver iodide smoke must be diffused by turbulence and lifted by the airflow into cloud regions where temperatures are colder than -10°C .

The ice crystals must have time to grow to a precipitable size and to fall to Earth before reaching the downdrafts that exist on the far side of the mountain ridge.

The meteorological conditions which are ideally suited for augmenting artificially the snowfall from a layer of orographic clouds are depicted in figure 4. The figure also shows the optimum location of ground-based silver iodide smoke generators upwind of the target area as well as the spreading of the silver iodide plume throughout the cloud by turbulent mixing. Although there are several seeding agents with suitable properties for artificial ice nuclei, silver iodide and lead iodide appear to be most effective. Owing to the poisonous effects of lead compounds, lead iodide has not had wide use. The optimum silver iodide particle concentration is a function of the temperature, moisture, and vertical currents in the atmosphere; it appears to be in the range from 5 to 100 nuclei per liter of cloud.⁵⁰ While the most common means of dispersing silver iodide in mountainous areas is by ground-based generators, other methods of cloud seeding make use of aircraft, rockets, and balloons.

In contrast to convective clouds, ice crystal formation in orographic clouds is thought to be static, depending primarily on cloud microphysics, and that orographic cloud seeding has little effect on the general patterns of wind, pressure, and temperature. On the other hand, clouds formed primarily by convection, such as summer cumulus or hurricane clouds, are believed to be affected dynamically by seeding as noted above in the discussion of modification of convective clouds.⁵¹ Since the lifting of the air in winter mountain storms is mainly caused by its passage over the mountain barrier, the release of latent energy accompanying this lifting has little effect upon the updraft itself. In convective cases, however, heat released through seeding increases buoyancy and lifting, with attendant effects on the wind and pressure fields. The static nature of the processes involved in orographic cloud modification therefore suggests that there is less chance that the storm dynamics downwind of the target area will be altered appreciably as a result of the modification activities.⁵²

⁵⁰ Ibid., p. 68.

⁵¹ See p. 68.

⁵² Ibid., pp. 70-71.

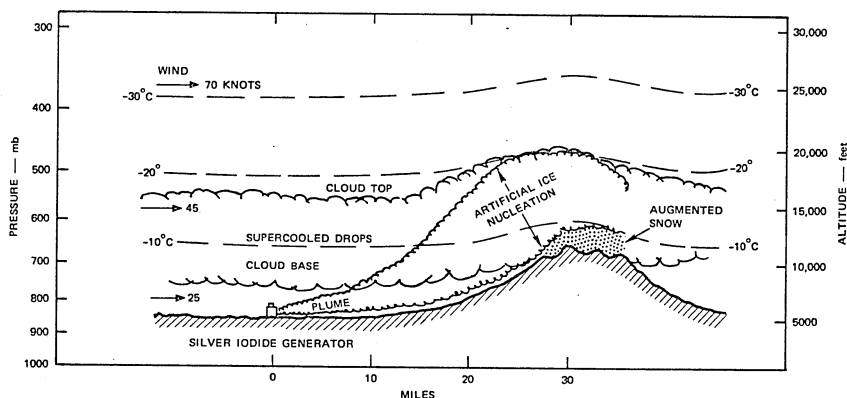


FIGURE 4.—Idealized model showing meteorological conditions that should lead to increased snowfall if clouds are seeded with silver iodide particles. (From Weisbecker, 1974.)

Orographic seeding experiments and seedability criteria

A randomized research weather modification program with winter orographic storms in central Colorado was initiated by Colorado State University in 1959. Data on precipitation and cloud physics were collected for 16 years under this Climax program, named for the location of its target area near Climax, Colo. Analysis of data has shown precipitation increases between 100 and 200 percent when the average temperatures of seeded clouds at the 500 millibar level were -20°C or warmer. When corresponding temperatures were -26°C to -21°C , precipitation changes ranged between -5 and $+6$ percent. For temperatures colder than -26°C , seeded cloud systems produced decreases in precipitation ranging from 22 to 46 percent.⁵³

While the results of Climax have provided some useful guidelines in establishing seedability criteria of certain cloud systems, it has been learned from other experimental programs that direct transfer of the Climax criteria to other areas is not warranted.⁵⁴ In particular, this nontransferability has been evident in connection with analysis of results from the Colorado River Basin Pilot Project, conducted from 1970 through 1975 in the San Juan Mountains of southwest Colorado, sponsored by the Bureau of Reclamation of the U.S. Department of the Interior.⁵⁵

Difficulties are frequently encountered in attempting to evaluate experimental cloud-seeding programs. A major problem in assessing results of all cold orographic cloud-seeding projects stems from the high natural variability of cloud properties. Frequent measurements are therefore required in order to monitor these properties carefully and consistently throughout the experiment. Another set of problems which have troubled investigators in a number of experimental programs follow from improper design. Such a deficiency can easily re-

⁵³ Hjermstad, Lawrence M., "San Juan and Climax." In proceedings of Special Weather Modification Conference; Augmentation of Winter Orographic Precipitation in the Western United States, San Francisco, Nov. 11-13, 1975, Boston, American Meteorological Society, 1975, p. 1 (abstract).

⁵⁴ Ibid., pp. 7-8.

⁵⁵ This project, part of Project Skywater of the Bureau of Reclamation, is discussed along with other programs of Federal agencies in chapter 5 of this report, see p. 254.

sult, for example, if insufficient physical measurements have been taken prior to establishment of the design of the experiment.⁵⁶

Under Project Skywater the Bureau of Reclamation has carried out an analysis of data from seven past weather modification projects in order to identify criteria which define conditions when cloud seeding will increase winter snowfall in mountainous terrain and when such seeding would have no effect or decrease precipitation. The seven projects examined in the study were conducted in the Rocky Mountains, in the Sierra Nevada, and in the southern coast range in California during the 1960's and 1970's, in areas which represent a wide range of meteorological and topographical conditions.⁵⁷

Figure 5 shows the locations of the seven projects whose results were analyzed in the Skywater study, and table 5 includes more detailed information on the locations and dates of seeding operations for these projects. General seedability criteria derived from this study were common to all seven projects, with the expectation that the criteria will also be applicable to all winter orographic cloud-seeding projects. While there have been other efforts to integrate results from several projects into generalized criteria, based only on a few meteorological variables, Vardiman and Moore considered 11 variables which depend on mountain barrier shapes and sizes and on characteristics of the clouds. Some of these variables are physically measurable while others are derived from simple computations.⁵⁸

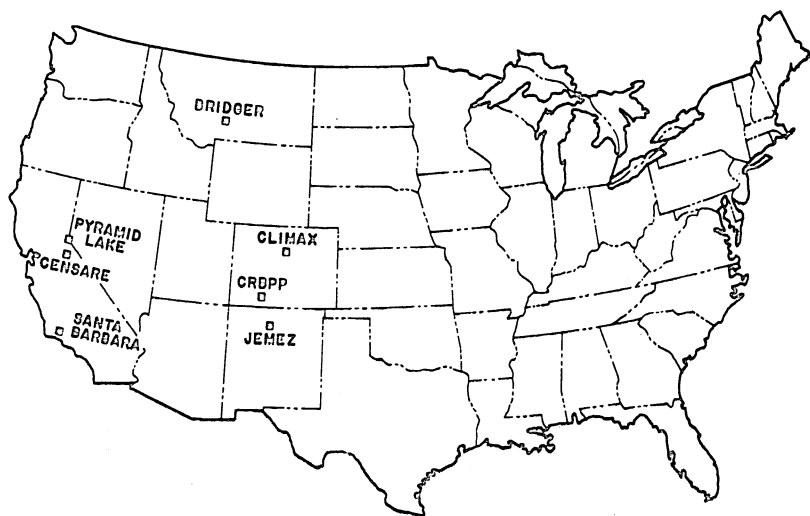


FIGURE 5.—Locations of winter orographic weather modification projects whose results were used to determine generalized cloud seeding criteria. (From Vardiman and Moore, 1977.

⁵⁶ Hobbs, Peter V., "Evaluation of Cloud Seeding Experiments; Some Lessons To Be Learned From the Cascade and San Juan Projects." In proceedings of Special Weather Modification Conference; Augmentation of Winter Orographic Precipitation in the Western United States, San Francisco, Nov. 11-13, 1975. Boston, American Meteorological Society, 1975, p. 31.

⁵⁷ Vardiman, Larry and James A. Moore, "Generalized Criteria for Seeding Winter Orographic Clouds." Skywater monograph No. 1, U.S. Department of the Interior, Bureau of Reclamation, Division of Atmospheric Water Resources Management, Denver, July 1977, 133 pp.

⁵⁸ Ibid., p. 15.

TABLE 5.—LIST OF WINTER OROGRAPHIC WEATHER MODIFICATION PROJECTS, GIVING SITES AND SEASONS OF OPERATIONS, USED IN STUDY TO DETERMINE GENERALIZED CLOUD SEEDING CRITERIA

[From Vardiman and Moore, 1977]

Project	Site	Seeding operations
Bridger Range Project (BGR).....	Rocky Mountains, Montana.....	1969-70 to 1971-72 (3 seasons).
Climax Project (CMX).....	Rocky Mountains, Colorado.....	1960-61 to 1969-70 (10 seasons).
Colorado River Basin Pilot Project (CRB).	Rocky Mountains, Colorado.....	1970-71 to 1974-75 (5 seasons).
Central Sierra Research Experiment (CSR).	Sierra Nevada, California.....	1968-69 to 1972-73 (5 seasons).
Jemez Mountains Project (JMZ).....	Rocky Mountains, New Mexico.....	1968-69 to 1971-72 (4 seasons).
Pyramid Lake Pilot Project (PYR).....	Sierra Nevada, California/Nevada.....	1972-73 to 1974-75 (3 seasons).
Santa Barbara Project (SBA).....	Southern Coast Range, California.....	1967-68 to 1973-74 (7 seasons).

Detailed analyses were conducted on four variables calculated from topography and vertical distributions of temperature, moisture, and winds. These are (1) the stability of the cloud, which is a measure of the likelihood that seeding material will reach a level in the cloud where it can effect the precipitation process; (2) the saturation mixing ratio at cloudbase, a measure of the amount of water available for conversion to precipitation; (3) the calculated cloud top temperature, a measure of the number of natural ice nuclei available to start the precipitation process; and (4) the calculated trajectory index, a measure of the time available for precipitation particles to form, grow, and fall to the ground.⁵⁹

Results of the study thus far are summarized below :

Seeding can increase precipitation at and near the mountain crest under the following conditions:

Stable clouds with moderate water content, cloud top temperatures between -10 and -30° C, and winds such that the precipitation particles would be expected to fall at or near the crest of the mountain barrier.

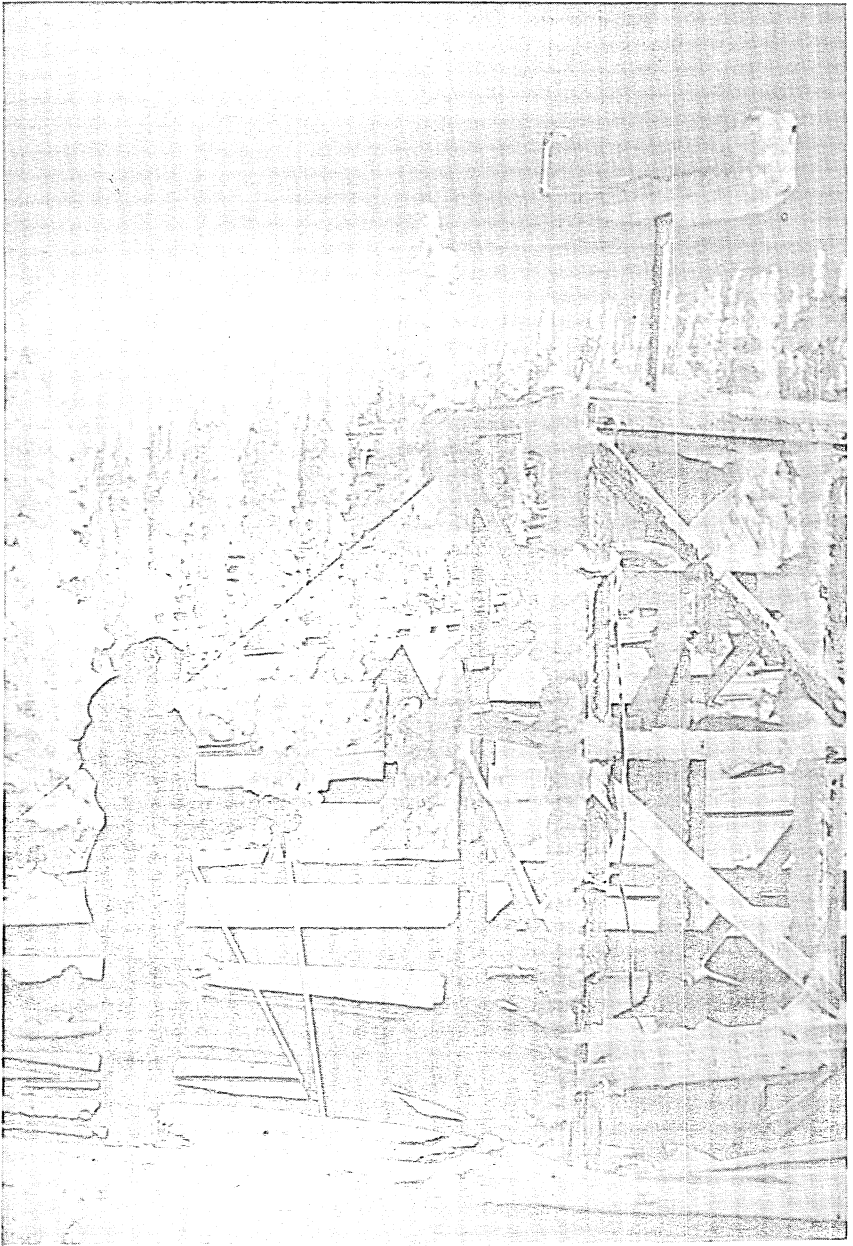
Moderately unstable clouds with moderate-to-high water content, cloud top temperatures between -10 and -30° C, and a crest trajectory for the precipitation.

Seeding appears to decrease precipitation across the entire mountain barrier under the following condition:

Unstable clouds with low water content, cloud top temperatures less than -30° C, and winds such that the precipitation particles would be carried beyond the mountain crest and evaporate before reaching the ground.⁶⁰

⁵⁹ Bureau of Reclamation, Division of Atmospheric Water Resources Management, "Summary Report: Generalized Criteria for Seeding Winter Orographic Clouds," Denver, March 1977, p. 1. (This is a summary of the report by Vardiman and Moore which is referenced above.)

⁶⁰ Ibid., pp. 1-2.



Rime ice conditions at sensing device which measures intensity of snowfall.
(Courtesy of the Bureau of Reclamation.)

Results quoted above represent only a portion of the analyses which are to be carried out. Seeding "window" bounds must be refined, and the expected effect must be converted into estimates of additional precipitation a target area might experience during a winter season. It is very unlikely that observed effects could have occurred by chance in view of the statistical tests which were applied to the data.⁶¹

Operational orographic seeding projects

For several decades commercial seeding of orographic clouds for precipitation augmentation has been underway in the western United States, sponsored by specific users which include utility companies, agricultural groups, and State and local governments. Much of the technology was developed in the late forties and early fifties by commercial operators, with some improvements since. The basic technique most often used involves release of silver iodide smoke, usually from ground-based generators, along the upwind slopes of the mountain where clouds are seeded, as shown schematically in figure 6. It is the opinion of Grant and Kahan that this basic approach still appears sound for seeding orographic clouds over many mountain barriers, but that in all aspects of these operating programs, there have been "substantial improvements" as a result of research and development programs.⁶² They summarized the following major deficiencies of past operational orographic seeding programs:

1. The lack of criteria for recognizing the seedability of specific clouds.
2. The lack of specific information as to where the seeding materials would go once they are released.
3. The lack of specific information as to downwind or broader social and economic effects from the operations.
4. The lack of detailed information on the efficiency of seeding generators and material being used for seeding clouds with differing temperatures.⁶³

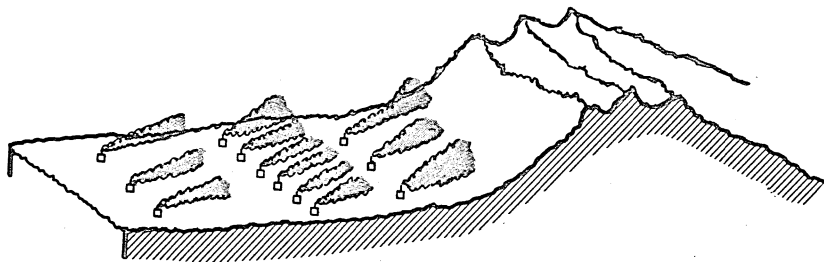


FIGURE 6.—Schematic view of silver iodide generators placed upwind from a target area in the mountains, where orographic clouds are to be seeded for precipitation enhancement. (From Weisbecker, 1974.)

⁶¹ Ibid., p. 2.

⁶² Grant and Kahan, "Weather Modification for Augmenting Orographic Precipitation," 1974, p. 307.

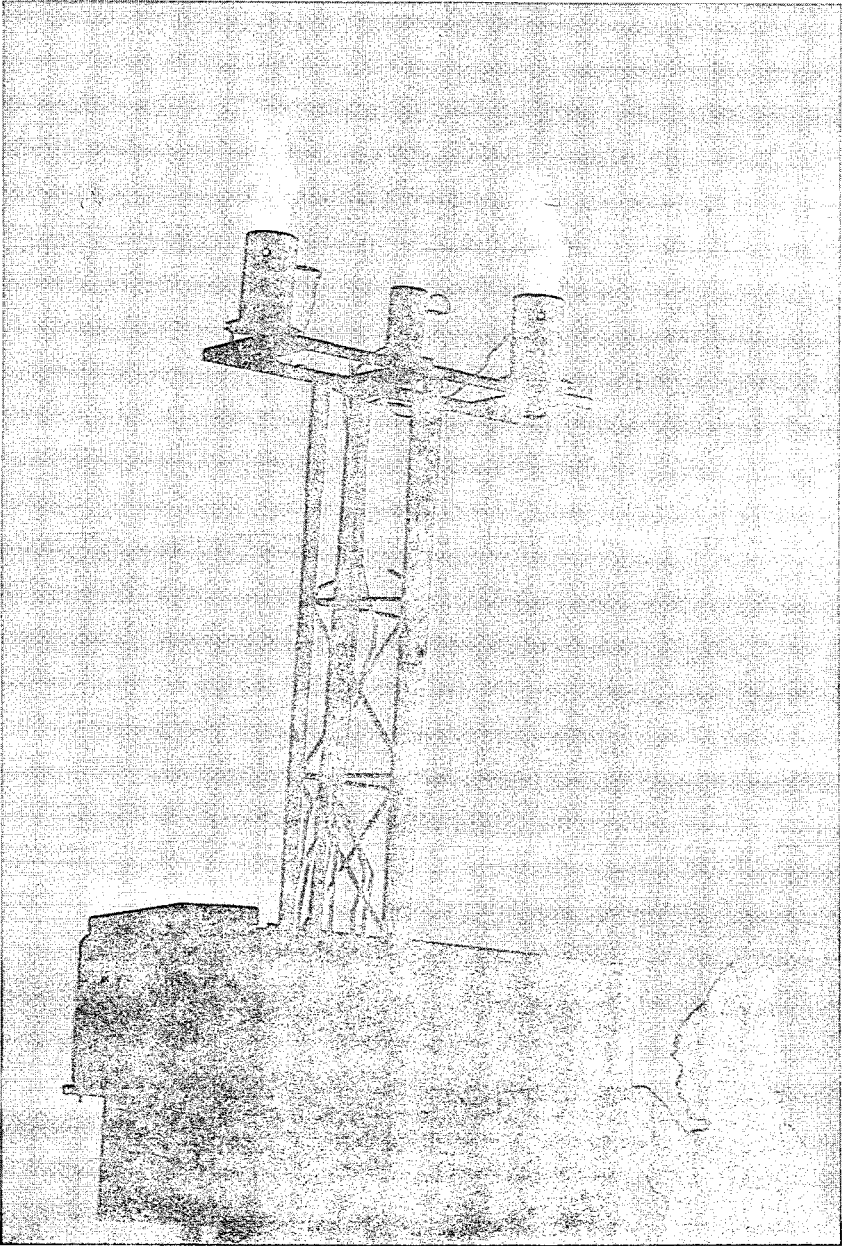
⁶³ Ibid., pp. 307-308.

Results achieved through orographic precipitation modification

Results from several projects in the western United States have shown that winter precipitation increases of 10 to 15 percent are possible if all suitable storms are seeded.⁶⁴ From randomized experiments at Climax, Colo., precipitation increases of 70 to 80 percent have been reported. These results, based on physical considerations, are representative of cases which have a high potential for artificial stimulation.⁶⁵

⁶⁴ U.S. Department of the Interior, Bureau of Reclamation, "Reclamation Research in the Seventies," Second progress report. A water resources technical publication research report No. 28, Washington, U.S. Government Printing Office, 1977, p. 2.

⁶⁵ National Academy of Sciences, "Climate and Food ; Climatic Fluctuation and U.S. Agricultural Production," 1976, p. 136.



Manually operated cloud seeding generator similar to those used in the Colorado River Basin Pilot Project. (Courtesy of the Bureau of Reclamation.)

HAIL SUPPRESSION

The hail problem

Along with floods, drought, and high winds, hail is one of the major hazards to agriculture. Table 6 shows the estimated average annual hail loss for various crops in the United States, for each of the 18 States whose total annual crop losses exceed \$10 million. Also included in the table are total losses for each crop and for each of the 18 States and the aggregate of the remaining States.

The following vivid description of a hailstorm conveys both a sense of its destructiveness and some notion of its capricious nature:

At the moment of its happening, a hailstorm can seem a most disastrous event. Crashing stones, often deluged in rain and hurled to the surface by wind, can create instant destruction. Picture windows may be broken, cars dented, or a whole field of corn shredded before our eyes.

Then quite quickly, the storm is over. Now the damage is before us, we perceive it to be great, and we vow to do something to prevent its happening again.

But what we have experienced is "our" storm. Hail did not happen perhaps a mile away. We may see another the same day, or never again. Thus, the concept of hail suppression is founded in a real or perceived need, but the assessment of this solution must be considered in terms of the nature of hail.⁶⁶

TABLE 6.—ESTIMATED AVERAGE HAIL LOSSES BY CROP, FOR STATES WITH LOSSES GREATER THAN \$10,000,000
[In millions of dollars]¹

State	Wheat	Corn	Soybeans	Cotton	Tobacco	Coarse grains ²	Fruits and vegetables	Total
Texas.....	16.7	31.3	1.5	49.1		16.1	2.8	86.2
Iowa.....	1.1	31.3	31.6			3.5	.3	66.8
Nebraska.....	16.8	27.2	4.1			4.7	7.7	60.5
Minnesota.....	2.3	17.6	18.7			7.5	2.2	48.3
Kansas.....	36.1	2.8	.9			4.7	1.3	45.8
North Dakota.....	28.8	.6	.8			12.5	1.6	44.3
North Carolina.....		.8	.3	.5	24.2	.1	1.9	28.0
Illinois.....	1.2	12.1	12.8			.5	.9	27.5
South Dakota.....	14.4	9.2	1.6			7.6	.1	27.4
Colorado.....	16.7	4.1				2.6	5.9	27.0
Montana.....	16.7	.1				5.0	2.2	24.0
Oklahoma.....	15.7	.2	.1	2.7		3.3		22.0
Kentucky.....		.4			15.9	.1	.3	16.8
Missouri.....	1.8	4.7	5.2	1.4	.3	.1	.7	14.2
South Carolina.....	.1	.6	1.1	1.7	6.4	.1	2.3	12.3
Idaho.....	2.6	.1				1.2	7.6	11.5
California.....	.2	.1		.5		1.8	8.5	11.1
Indiana.....	.9	3.8	4.7		.4	.3	.7	10.8
Other States.....	8.4	7.8	7.6	18.3	17.9	15.1	20.4	95.5
Total.....	172.0	123.5	91.0	74.2	65.1	86.6	67.4	680.0

¹ 1973 production and price levels.

² Coarse grains: Barley, rye, oats, sorghum.

Source: "National Hail Research Experiment" from Boone (1974).

A major characteristic of hail is its enormous variability in time, space, and size. Some measure of this great variability is seen in figure 7, which shows the average annual number of days with hail at points within the continental United States. The contours enclose points with equal frequency of hail days.⁶⁷

⁶⁶ Changnon, Stanley A., Jr., Ray Jay Davis, Barbara C. Farhar, J. Eugene Haas, J. Lorena Ivens, Marvin V. Jones, Donald A. Klein, Dean Mann, Griffith M. Morgan, Jr., Steven T. Sonka, Earl R. Swanson, C. Robert Taylor, and Jon Van Blokland, "Hail Suppression: Impacts and Issues." Final report—"Technology Assessment of the Suppression of Hail (TASH)." Urbana, Ill. Illinois State Water Survey, April 1977 (sponsored by the National Science Foundation, Research Applied to National Needs Program), p. 9.

⁶⁷ Ibid.

Hail forms in the more active convective clouds, with large vertical motions, where large quantities of water vapor condense under conditions in which large ice particles can grow quickly. The kinds of convective clouds from which hail can be formed include (1) supercells (large, quasi-steady-state, convective storms), (2) multicell storms (active convective storms with multiple cells), (3) organized convective storms of squall lines or fronts, and (4) unstable, highly convective small cumuli (primarily occurring in spring).⁶⁸ While hail generally occurs only in thunderstorms, yet only a small proportion of the world's thunderstorms produce an appreciable amount of hail. Based upon several related theories, the following description of the formation of hail is typical:

Ice crystals or snowflakes, or clumps of snowflakes, which form above the zone of freezing during a thunderstorm, fall through a stratum of supercooled water droplets (that is, water droplets well below 0° C). The contact of the ice or snow particles with the supercooled water droplets causes a film of ice to form on the snow or ice pellet. The pellet may continue to fall a considerable distance before it is carried up again by a strong vertical current into the stratum of supercooled water droplets where another film of water covers it. This process may be repeated many times until the pellet can no longer be supported by the convective updraft and falls to the ground as hail.⁶⁹

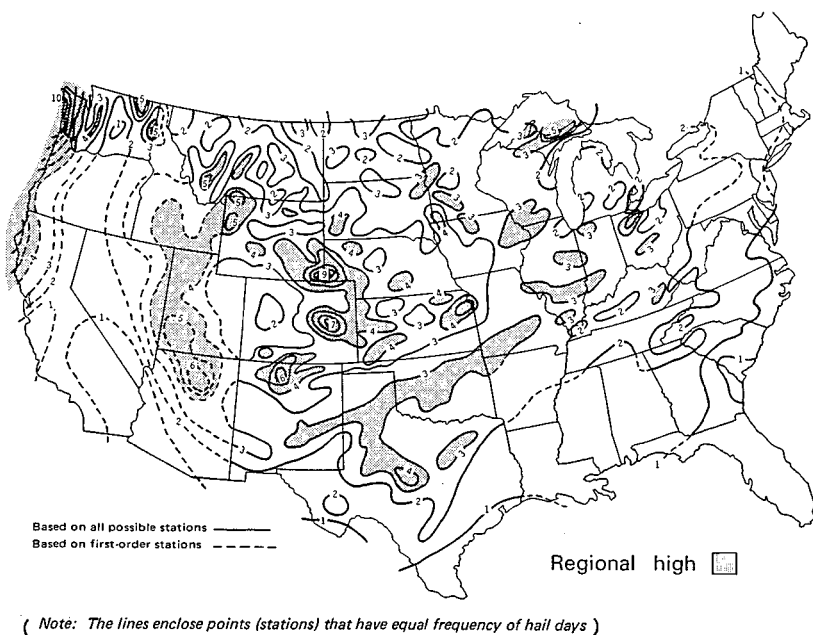


FIGURE 7.—Average annual number of days with hail at a point, for the contiguous United States. (From Changnon, et al., TASH, 1977.)

⁶⁸ National Academy of Sciences, "Climate and Food; Climatic Fluctuation and U.S. Agricultural Production," 1976, p. 141.

⁶⁹ Koeppe, Clarence E. and George C. de Long, "Weather and Climate," New York, McGraw-Hill, 1958, pp. 79-80.

Modification of hail

According to D. Ray Booker, "Hail modification seeding has been done operationally for decades in the high plains of the United States and in other hail prone areas of the world. Thus, there appears to be a significant market for a hail-reduction technology."⁷⁰ In the United States most attempts at hail suppression are conducted by commercial seeders who are under contract to State and county governments and to community associations. There are also extensive hail suppression operations underway in foreign countries. Although some successes are reported, many important questions are still unanswered with regard to mitigation of hail effects, owing largely to lack of a satisfactory scheme for evaluation of results from these projects.

In theory, it should be possible to inhibit the formation of large ice particles which constitute hailstones by seeding in order to increase the number of freezing nuclei so that only smaller ice particles will develop. This would then leave the cloud with insufficient precipitation water to allow the accretion of supercooled droplets and the formation of hail of damaging size. This simplistic rationale, however, does not provide insight into the many complications with which artificial hail suppression is fraught; nor does it explain the seemingly capricious responses of hailstorms to seeding and the inconsistent results which characterize such modification attempts. As with all convective systems, the processes involved are very complex. They are controlled by the speed of movement of the air parcels and precipitation particles, leading to complicated particle growth, evaporation, and settling processes.⁷¹ As a result, according to Changnon, the conclusions from various hail suppression programs are less certain than from those for attempts to enhance rain from convective clouds, and they are best labeled "contradictory."⁷²

Changnon identifies two basic approaches that have been taken toward hail modification:

Most common has been the intensive, high rates of seeding of the potential storm with silver iodide in an attempt to transform nearly all of the supercooled water into ice crystals, or to "glaciate" the upper portion of the clouds. However, if only part of the supercooled water is transformed into ice, the storm could actually be worsened since growth by accretion is especially rapid in an environment composed of a mixture of supercooled drops and ice crystals. Importantly, to be successful, this frequently used approach requires massive seeding well in advance of the first hailstone formation.

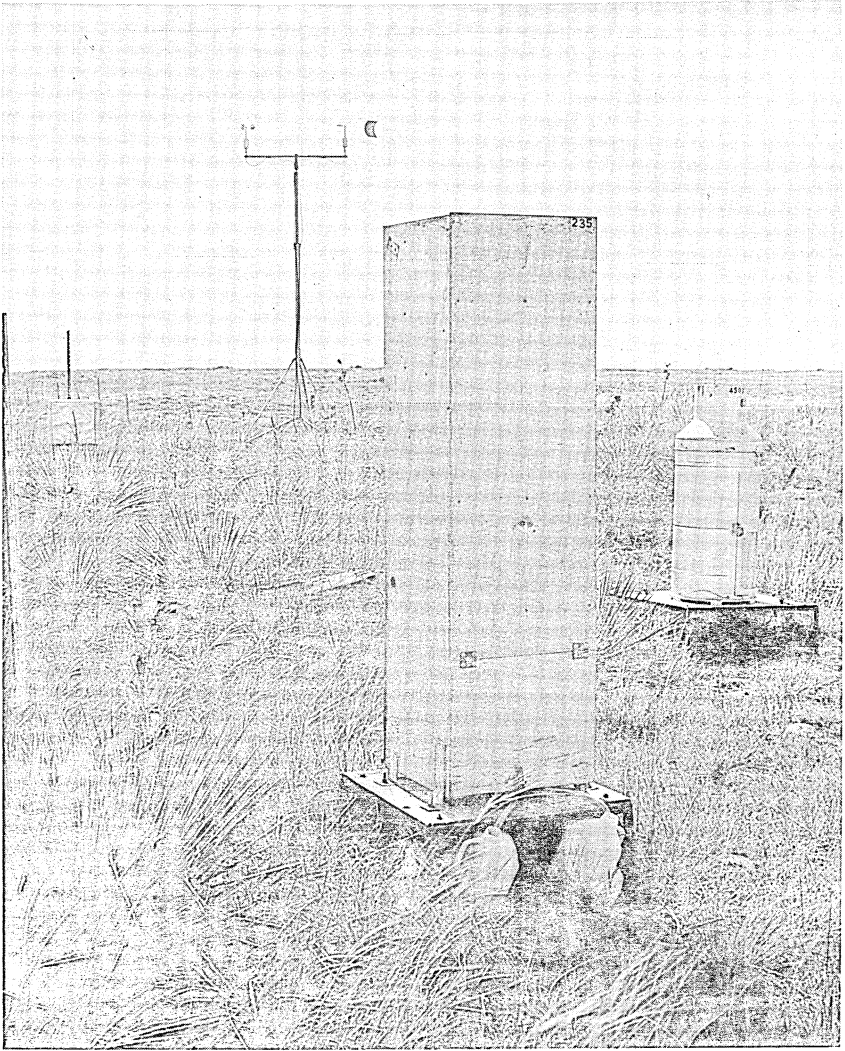
The second major approach has been used in the Soviet Union and * * * in the National Hail Research Experiment in Colorado. It involves massive seeding with silver iodide, but only in the zone of maximum liquid water content of the cloud. The hope is to create many hailstone embryos so that there will be insufficient supercooled water available to enable growth to damaging stone sizes.⁷³

⁷⁰ Booker, D. Ray, "A Marketing Approach to Weather Modification," background paper prepared for the U.S. Department of Commerce Weather Modification Advisory Board, Feb. 26, 1977, p. 4.

⁷¹ National Academy of Sciences, "Climate and Food; Climatic Fluctuation and U.S. Agricultural Production," 1976, p. 143.

⁷² Changnon, "Present and Future of Weather Modification; Regional Issues," 1975, p. 162.

⁷³ *Ibid.*



Precipitation instrument site, including, from left to right, hailcube, anemometer, rain/hail separator, and Belfort weighing precipitation gage. (Courtesy of the National Science Foundation.)

Hail seeding technologies

The most significant field programs in hail suppression during recent years have included those conducted in the Soviet Union, in Alberta, in South Africa, and in northeastern Colorado (the National Hail Research Experiment). In the course of each of these projects, some of which are still underway, various procedural changes have been initiated. In all of them, except that in South Africa, the suppression techniques are based on increasing the number of hail embryos by

seeding the cloud with ice nuclei. Usually, the seeding material is silver iodide, but the Russians also use lead iodide, and on occasion other agents such as sodium chloride and copper sulfate have been used. The essential problems in seeding for hail suppression are related to how, when, and where to get the seeding agent into potential hail clouds and how to identify such clouds.⁷⁴

Soviet suppression techniques are based on their hypothesis that rapid hail growth occurs in the "accumulation zone," just above the level of maximum updraft, where liquid water content can be as great as 40 grams per cubic meter. To get significant hail, the maximum updraft should exceed 10 to 15 meters per second, and the temperature in this zone must be between 0 and -25° C. Upper large droplets freeze and grow, combining with lower large droplets, and an increase in particle size from 0.1 cm to 2 or 3 cm can occur in only 4 to 5 minutes. In the several Russian projects, the seeding agent is introduced at selected cloud heights from rockets or antiaircraft shells; the number of volleys required and the position of injection being determined by radar echo characteristics and past experience in a given operational region.⁷⁵

In other hail suppression projects, seeding is most frequently carried out with aircraft, from which flares containing the seeding agent are released by ejection or dropping. Each flare may contain up to 100 grams of silver iodide; and the number used as well as the spacing and height of ignition are determined from cloud characteristics as well as past experience in a given experiment or operation. In each case it is intended to inject the seeding material into the supercooled portion of the cloud.

Evaluation of hail suppression technology

It appears that mitigation of the effects of hail has some promise, based on the collection of total evidence from experiments and operations around the world. In the Soviet Union, scientists have been reporting spectacular success (claims of 60 to 80 percent reduction)⁷⁶ in hail suppression for nearly 15 years; however, their claims are not universally accepted, since there has not been careful evaluation under controlled conditions. Hail-seeding experiments have had mixed results in other parts of the world, although a number of commercial seeders have claimed success in hail damage reduction, but not with convincing evidence.⁷⁷

Successful hail suppression reports have come from a number of operational programs in the United States as well as from weather modification activities in the Soviet Union and in South Africa. Often the validity of these results is questionable in view of deficiencies in project design and data analysis; nevertheless, the cumulative evidence suggests that hail suppression is feasible under certain conditions. There are also reports of negative results, for example, in foreign programs and in the National Hail Research Experiment in the United

⁷⁴ Changnon, Stanley A., Jr., and Griffith M. Morgan, Jr., "Design of an Experiment To Suppress Hail in Illinois," Illinois State Water Survey, ISWS/B-61/76, Bulletin 61, State of Illinois, Department of Registration and Education, Urbana, 1976, pp. 82-83.

⁷⁵ *Ibid.*, p. 83.

⁷⁶ Changnon, "Present and Future of Weather Modification," 1975, p. 162.

⁷⁷ Battan, Louis J. statement submitted to Subcommittee on Environment and Atmosphere, Committee on Science and Technology, U.S. House of Representatives, at hearings, June 18, 1976, pp. 7-8.

States, which indicate that under some conditions seeding induces increased hail.⁷⁸

Atlas notes that this apparent dichotomy has until recently been attributed to different approaches to the techniques and rates of seeding. However, he observes that both positive and negative results have been obtained using a variety of seeding methods, including ground- and cloud-based generators, flares dropped from above the cloud top, and injection by rockets and artillery.⁷⁹ In discussing the reasons for increased hail upon seeding, Atlas states:

There are at least four physical mechanisms by which seeding may produce increased hail. Two of these occur in situations in which the rate of supply of supercooled water exceeds that which can be effectively depleted by the combination of natural and artificially produced hail embryos. This may occur in supercell storms and in any cold-base storm in which the embryos are graupel rather than frozen raindrops. Moreover, present seeding methods are much more effective in warm-base situations in which the hail embryos are frozen raindrops. Increased hail is also probable when partial glaciation of a cloud is produced and the hail can grow more effectively upon the ice-water mixture than upon the supercooled water alone. Similarly, increases in the amount of hail may occur whenever the additional latent heat resulting from nucleation alters the undraft profile in such a manner as to increase its maximum velocity or to shift the peak velocity into the temperature range from -20° to -30° C, where the accreted water can be more readily frozen. A probable associated effect is the redistribution of precipitation loading by the combination of an alternation in the updraft velocity and the particle sizes such that the hail embryos may grow for longer durations in a more favorable growth environment.⁸⁰

Surveys of hail suppression effectiveness

Recently, Changnon collected information on the effectiveness of hail suppression technology from three different kinds of sources. One set of data was based on the results of the evaluations of six hail suppression projects; another was the collection of the findings of three published assessments of hail modification; and the third was obtained from two opinion surveys conducted among weather modification scientists.⁸¹ The principal statistics on the estimated capabilities for hail suppression from each of these groups of sources are summarized in table 7. Where available, the estimated change in rainfall accompanying the hail modification estimates are also included. Such rainfall changes might have been sought intentionally as part of a hail suppression activity or might result simply as a byproduct of the major thrust in reducing hail. In the table, a plus sign indicates an estimated percentage increase in hail and/or rainfall while a minus sign signifies a percentage decrease.

The six evaluations in part A of table 7 are from both experimental and operational projects, each of which was conducted for at least 3 years in a single locale and in each of which aircraft seeding techniques were used. Thus, the results of a number of earlier experiments, using ground-based seeding generators, were not considered in the estimations. Furthermore, change in hail due to suppression activities was defined on the basis of crop-loss statistics rather than on the basis of frequency of hail days, since Changnon does not consider the latter,

⁷⁸ Atlas, David, "The Paradox of Hail Suppression," *Science*, vol. 195, No. 4274, Jan. 14, 1977, p. 195.

⁷⁹ *Ibid.*

⁸⁰ *Ibid.*, pp. 195-196.

⁸¹ Changnon, Stanley A., Jr., "On the Status of Hail Suppression," *Bulletin of the American Meteorological Society*, vol. 58, No. 1, Jan. 1977, pp. 20-28.

along with other criteria such as number and size of hailstones, hail mass, and radar echo characteristics, to be a reliable indicator.⁸² Note that five of the six projects listed indicate a hail suppression capability ranging from 20 percent to 48 percent. Changnon notes, however, that most of these results are not statistically significant at the 5 percent level, but that most scientists would classify the results as "optimistic."⁸³

TABLE 7.—Status of Hail Suppression and Related Rainfall Modification
(Based on information from Changnon. On the Status of Hail Suppression.
1977.)

A. BEST ESTIMATES FROM PROJECT EVALUATIONS

1. Texas: Hail modification was -48 percent (crop-loss cost value) ; no change in rainfall.
2. Southwestern North Dakota: Hail modification was -32 percent (crop-hail insurance rates) ; no rain change information available.
3. North Dakota pilot project: Hail modification was -30 percent (a composite of hail characteristics, radar, and crop-loss data) ; change in rainfall was +23 percent.
4. South Africa: Hail modification was -40 percent (crop-loss severity ; change in rainfall was -4 percent.
5. South Dakota "Statewide" project: Hail modification was -20 percent (crop loss) ; increase in rainfall was +7 percent.
6. National hail research experiment in Colorado :
Increase in hail mass was +4 percent to +23 percent, with median of +23 percent :
Increase in rainfall was +25 percent.

B. PUBLISHED ASSESSMENTS

1. American Meteorological Society: Positive but unsubstantiated claims and growing optimism.
2. National Academy of Sciences: 30 to 50 percent reductions in U.S.S.R. and 15 percent decreases in France—neither result proven by experimentation.
3. Colorado State University Workshop :
-30 percent modification nationwide ;
-30 percent modification in the High Plains, with ± 10 -percent change in rain ; unknown results in the Midwest ; also unknown rainfall effects.

C. OPINION SURVEYS (MEDIAN VALUES)

1. Farhar-Grant questionnaire (214 answers) : -25 percent crop-hail damage nationwide, although majority—59 percent—admit they do not know.
2. Illinois State Water Survey questionnaire (63 answers) :
-30 percent hail loss, with +15 percent rain increase in the Great Plains ;
-20 percent hail loss, with +10 percent rain increase in the Midwest.

The results, shown in part B of table 7, from the recent published assessments of capability in hail suppression reveal a position of "guarded optimism;" however, there is no indication of definitive proof of hail suppression contained in these assessments.⁸⁴ These published assessments are comprised of a statement on the status of weather modification by the American Meteorological Society,⁸⁵ the conclusions of a study on the progress of weather modification by the

⁸² Ibid., p. 22.

⁸³ Ibid., p. 26.

⁸⁴ Ibid.

⁸⁵ American Meteorological Society, "Policy Statement of the American Meteorological Society on Purposeful and Inadvertent Modification of Weather and Climate," Bulletin of the American Meteorological Society, vol. 54, No. 7, July 1973, pp. 694-695.

National Academy of Sciences,⁸⁶ and a report on a workshop at Colorado State University on weather modification and agriculture.⁸⁷

The third view (part C, table 7) resulting from two opinion surveys, indicates wide-ranging but basically "bipolar" attitudes among the scientists surveyed. The majority of the experts queried felt that a hail suppression capability could not be identified; however, a sizable minority were of the opinion that a moderate capability for modifying hail (greater than 20-percent decrease) does now exist. Changnon says that the results of these opinion surveys show at best that the consensus must be considered to be a pessimistic view of a hail suppression capability.⁸⁸

In his conclusions on the status of hail suppression technology, Changnon states:

These three views of the current status of hail suppression, labeled as (1) optimistic, (2) slightly optimistic, and (3) pessimistic, reflect a wide range of opinion and results. Clearly, the present status of hail suppression is in a state of uncertainty. Reviews of the existing results from 6 recent operational and experimental hail suppression projects are sufficiently suggestive of a hail suppression capability in the range of 20 to 50 percent to suggest the need for an extensive investigation by an august body of the hail suppression capability exhibited in these and other programs.

One of the necessary steps in the wise experimentation and future use of hail suppression in the United States is to cast the current status in a proper light. This can only be accomplished by a vigorous in-depth study and evaluation of the results of the recent projects.⁸⁹

Conclusions from the TASH study

Sponsored by the Research Applied to National Needs program of the National Science Foundation, a major technology assessment of hail suppression in the United States was conducted from 1975 through 1977, by an interdisciplinary research team.⁹⁰ This Technology Assessment of the Suppression of Hail (TASH) study was intended to bring together all of the considerations involved in the application of hail suppression, in the present and in the future, to ascertain the net value of such technology to society. The goals of the study were:

To describe the current knowledge of hail suppression.

To identify long-range expectations for such a technology.

To estimate the societal impacts that might be generated by its wide use.

To examine public policy actions that would most equitably direct its beneficial use.

From its interdisciplinary study of hail suppression and its impacts the TASH team reached the following broad conclusions on the effects of hail and on the potential technology for suppression of hail:

The United States experiences about \$850 million in direct crop and property hail losses each year, not including secondary losses from hail. The key characteristic of hail is its enormous variability in size, time, and space.

Among the alternative ways of dealing with the hail problem, including crop insurance, hail suppression, given a high level of development, appears to be the most promising future approach in high hail loss areas. Economic benefits from effective hail suppression vary by region of the country, with the most benefit to

⁸⁶ National Academy of Sciences, National Research Council, Committee on Atmospheric Sciences, "Weather and Climate Modification: Problems and Progress," Washington, D.C., 1973, pp. 100-106.

⁸⁷ Grant and Reid, "Workshop for an Assessment of the Present and Potential Role of Weather Modification in Agriculture Production," 1975, pp. 33-45.

⁸⁸ Changnon, "On the Status of Hail Suppression," 1977, p. 26.

⁸⁹ *Ibid.*, pp. 26-27.

⁹⁰ Changnon, et al., "Hail Suppression: Impacts and Issues," Technology Assessment of the Suppression of Hail (TASH), 1977, 432 pp.

be derived in the Great Plains area. Any alterations in rainfall resulting from hail suppression would importantly affect its economic consequences.

The effects of cloud seeding on rainfall are more significant than its effects on hail from economic and societal standpoints.

At the present time there is no established hail suppression technology. It may be possible to reduce damaging hail about 25 percent over the growing season in a properly conducted project.

Reducing the scientific uncertainties about hail suppression will require a substantial commitment by the Federal Government for long-term funding of a systematic, well-designed program of research. For the next decade or so, monitoring and evaluation of operational programs will be important.

Benefit-cost analysis revealed that investment in development of the high-level technology would result in a ratio of 14:1, with the present value of benefits estimated to total \$2.8 billion for 20 years. The low-level technology showed a negative benefit-cost ratio. Research and development to provide the high-level technology is the best choice from an economic standpoint; a minimal level of support would be nonbeneficial. In a word, if we are going to develop hail suppression technology, we would need to do it right.

Effective hail suppression will, because of the hail hazard, technological approach, patterns of adoption, and institutional arrangements, lead to regionally coherent programs that embrace groups of States, largely in the Great Plains.

Some would gain and others would lose from widespread application of an effective hail suppression technology. Farmers within adopting regions would receive immediate benefits from increased production. After several years this economic advantage would be diminished somewhat, but increased stability of income would remain. Farmers growing the same crops outside the adopting areas would have no advantages and would be economically disadvantaged by commodity prices lower than they would have been with no hail suppression. The price depressing effects result from increased production in adopting areas. Consumers would benefit from slightly decreased food prices. The impacts generated by a highly effective technology include both positive and negative outcomes for various other stake-holder groups in the Nation. For the Nation as a whole, the impacts would be minor and beneficial. On balance, the positive impacts outweigh the negative impacts if a high-level technology can be developed.

An adequate means of providing equitable compensation on an economically sound basis for persons suffering from losses due to cloud seeding has not been developed. Some better procedure for compensating losers will be necessary. In addition, present decision mechanisms and institutional arrangements are inadequate to implement the technology in a socially acceptable manner. Some mechanism for including potential opponents in the decisionmaking process will be required.

It is unlikely that widespread operational hail suppression programs would have serious adverse environmental impacts, although lack of sufficient knowledge indicates that adverse impacts should not be ruled out. Long-term environmental effects are not known at the present time.⁹¹

DISSIPATION OF FOG AND STRATUS CLOUDS

Fog poses a hazard to man's transportation activities, particularly to aviation, where as a result of delays air carriers lose over \$80 million annually. Highway accidents attributed to fog are estimated to cost over \$300 million per year.⁹² Most often the impetus to develop effective fog and stratus cloud dispersal capabilities has come from the needs of commercial and military aircraft operations.

There are two basic kinds of fog, and the suppression of each requires a different approach. Supercooled fog and stratus clouds are comprised of liquid water droplets whose temperature is below freez-

⁹¹ Farhar, Barbara C., Stanley A. Changnon, Jr., Earl R. Swanson, Ray J. Davis, and J. Eugene Haas, "Hail Suppression and Society: Summary of Technology Assessment of Hail Suppression," Urbana, Ill., "Illinois State Water Survey, June 1977," pp. 21-22. (This document is an executive summary of the technology assessment by Changnon, et al., "Hail Suppression: Impacts and Issues.")

⁹² National Oceanic and Atmospheric Administration, "Summary Report: Weather Modification; Fiscal Years 1969, 1970, 1971," Rockville, Md., May 1973, p. 72.

ing (i.e., 0° C or below). Supercooled fogs account for only about 5 percent of all fog occurrences in the United States, although they are prevalent in certain parts of northeastern and northwestern North America. The remainder of North American fogs are warm fogs (water droplets warmer than 0° C).⁹³ Although cold fog has been amenable to modification, so that there essentially exists an operational technology for its dissipation, practical modification of warm fogs, on an economical basis, has not yet been achieved.

Cold fog modification

Dispersal of cold fog by airborne or ground-based techniques has been generally successful and has become an operational weather modification technology. In the United States cold fog dispersal operations have been conducted, for example, by commercial airlines, usually with dry ice as the seeding agent. The U.S. Air Force has also operated ground-based liquid propane systems, at domestic and foreign bases, which have been effective in dissipating cold fog over runways, thus reducing flight delays and diversions.⁹⁴ Conducted largely at airports, cold fog suppression is usually accomplished using aircraft, which drop various freezing agents, such as dry ice or silver iodide as they fly over the fog-covered runways. The agents initiate ice crystal formation and lead to precipitation of the growing crystals.⁹⁵ Ground-based systems for cold fog dispersal have also been used and have some advantages over airborne systems. Such a system can operate continuously for extended time periods more economically and more reliably.

Warm fog modification

The remainder of North American fogs are "warm fogs" for which a suitable dispersal capability remains to be developed. Crutchfield summarizes the status of warm fog dispersal technology and its economic potential:

The much more extensive warm fogs which cause delays, accidents, and costly interruptions to every type of transportation have proved intractable to weather modification thus far. Some success has been achieved on occasion by heavy seeding with salt and other materials, but results have not been uniformly good, and the materials used have presented environmental problems in the areas treated. Heating airport runways has been of some benefit in dealing with warm fog, but at present is not generally effective in cost-benefit terms and can interrupt air traffic.

Nevertheless, the research and technology problems involved in the dispersal of warm fog appear to be of manageable proportions, and the benefits from an environmentally acceptable and predictable technique for dealing with warm fog would be of very real interest in terms of economic gain.⁹⁶

A number of field techniques have been attempted, with some measure of success, for artificial modification of warm fogs. Seeding is one technique, where the seeding agents are usually hygroscopic particles, solution drops, or both. There are two possible desired effects of seeding warm fogs, one being the evaporation of fog droplets, resulting in visibility improvement. A second desired effect of seeding, results from the "coalescence" process, in which the solution droplets, falling

⁹³ Changnon, "Present and Future of Weather Modification," 1975, p. 165.

⁹⁴ National Oceanic and Atmospheric Administration "Summary Report: Weather Modification; Fiscal Year 1973." Rockville, Md., December 1974, pp. 39-40.

⁹⁵ Changnon, "Present and Future of Weather Modification," 1975, p. 165.

⁹⁶ Crutchfield, James A., "Weather Modification: The Economic Potential." Paper prepared for U.S. Department of Commerce Weather Modification Advisory Board. University of Washington, Seattle, May 1977, pp. 5-6.

through the fog layer, collect the smaller fog droplets, increasing visibility as the fog particles are removed in the fallout.⁹⁷ There is a wide diversity of hygroscopic particles which can and have been used for warm fog dissipation. Sodium chloride and urea are the most common, but others have included polyelectrolyte chemicals, an exceedingly hygroscopic solution of ammonium-nitrate urea, and some biodegradable chemicals. Seeding particle size is critical to the effectiveness of a warm fog dispersal attempt; it has been found that poly-dispersed particles (i.e., material with a distribution of particle sizes) are more effective in inducing fog modification than are extra fine particles of uniform size, which were only thought to be optimum in earlier experiments. Other problems which are the subject of continuing study relate to the seeding procedures, including the number of flights, number of aircraft to be used, and flight patterns in accordance with the local terrain and wind conditions. One of the most difficult operational problems in the seeding of warm fog is that of targeting. One solution to this problem, suggested by the Air Force, is the implementation of wide-area seeding instead of single-line seeding, which is so easily influenced by turbulence and wind shear.⁹⁸

Another technique for dissipation of warm fog makes use of heating. The physical principle involved is the vaporization of the water droplets through introduction of sufficient heat to vaporize the water and also warm the air to such a temperature that it will hold the additional moisture and prevent condensation. Knowing the amount of liquid water in the atmosphere from physical measurements, the necessary amount of heat energy to be injected can be determined.⁹⁹ The feasibility of this approach was first demonstrated in England during World War II, when it was necessary to fly aircraft in all kinds of weather in spite of frequent fogbound conditions in the British Isles. The acronym FIDO, standing for Fog Investigations Dispersal Of, was applied to a simple system whereby fuel oil in containers placed along the runways was ignited at times when it was necessary to land a plane in the fog. Although burning as much as 6,000 gallons of oil for a single airplane landing was expensive and inefficient, it was justified as a necessary weather modification technique during wartime.^{99a}

Initial and subsequent attempts to disperse fog by burning liquid fuel were found to be hazardous, uneconomical, and sometimes ineffective, and, as a result, not much was done with this heating technique until the French revised it, developing the Turboclair method for dissipating fog by heating with underground jet blowers. After 10 years of development and engineering testing, the system was tested successfully by the Paris Airport Authority at Orly Airport. This program has given a new interest and stimulated further research and development of this technique both in the United States and elsewhere. In the United States, the Air Force conducted Project Warm Fog to test the effectiveness of heating to remove warm fog. It is clear that this method is promising; however, further studies are needed.¹

⁹⁷ Moschandreas, Demetrios J., "Present Capabilities to Modify Warm Fog and Stratus," Geomet, Inc., report No. EF-300. Technical report for Office of Naval Research and Naval Air Systems Command, Rockville, Md., Jan. 18, 1974, p. 13.

⁹⁸ Ibid., pp. 16-17.

⁹⁹ Ibid., pp. 24, 30.

^{99a} Halacy, Daniel S., Jr., "The Weather Changers," New York, Harper and Row, 1968, pp. 105-107.

¹ Moschandreas, "Present Capabilities to Modify Warm Fog and Stratus," 1974, pp. 30-40.

Research and development on warm fog dispersal systems has continued under sponsorship of the U.S. Air Force, using both passive heat systems, and thermokinetic systems which combine both heat and mechanical thrust. A thermokinetic system, known as the Warm Fog Dispersal System (WFDS), consists of three components: The combustors, the controls, and the fuel storage and distribution hardware. Testing of the WFDS by the Air Force is to be conducted during late 1978 and 1979 at Otis Air Force Base in Massachusetts, after which it is to be installed and operational at an Air Force base by 1982.² Discussion of the Air Force development program and of the concurrent studies and interest on the Federal Aviation Administration in this thermokinetic fog dispersal system is found in chapter 5 of this report.³

There have been attempts to evaporate warm fogs through mechanical mixing of the fog layer with warmer, drier air from above. Such attempts have been underway using the strong downwash from helicopters; however, such a technique is very costly and would likely be employed only at military installations where a number of helicopters might be available.

The helicopters hover or move slowly in the dry air above the fog layer. Clear dry air is moved downward into the fog by the circulation of the helicopter rotors. The mixture of dry and cloudy air permits the fog to evaporate, and in the fog layer there is created an opening whose size and lifetime are determined by the meteorological conditions in the area, by the flight pattern, and by the kind of helicopter.

Conclusions reached by scientists involved in a series of joint U.S. Air Force-Army research projects using helicopters for fog dispersal follow:

The downwash method by a single helicopter can clear zones large enough for helicopter landing if the depth of the fog is less than 300 feet (100 meters).

Single or multiple helicopters with flight patterns properly orchestrated can maintain continuous clearings appropriate for aircraft takeoff and landing in fogs of less than 300 feet (100 meters) deep.⁴

In addition to the more commonly applied experimental techniques, such as seeding, heating, and mechanical mixing, other attempts have been made to disperse warm fogs. These have included the injection of ions or charged drops into the fog and the use of a laser beam to clear the fog. Further research is needed before definitive results can be cited using these methods.⁵

Table 8 is a summary of research projects on warm fog dispersal which had been conducted by various organizations in the United States between 1967 and 1973. Note that, in addition to field experiments, research included modeling, field measurements and observations of fog, chamber tests, statistical interpretation, model evaluation, and operational assessment.

On the basis of his study of research projects through 1973 and claims projected by the scientists involved in the various warm fog

² Kunkel, Bruce A., "The Design of a Warm Fog Dispersal System." In preprints of the Sixth Conference on Planned and Inadvertent Weather Modification, Champaign, Ill., Oct. 10-13, 1977. Boston, American Meteorological Society, 1977, pp. 174-176.

³ See pp. 305 and 308.

⁴ Moschandreas, "Present Capabilities To Modify Warm Fog and Stratus," 1974, p. 45.

⁵ Ibid., p. 14.

modification programs, Demetrios Moschandreas formulated the following conclusions on warm fog dispersal:

Seeding with hygroscopic particles has been successful; however, targeting problems would require the wide-area approach to seeding. Urea has also been projected as the agent which is most effective and least harmful to the environment.

The heating technique is very promising and very efficient; studies for further verification of its capabilities are in order.

The helicopter technique by itself has not been as promising as the combination of its use with hygroscopic seeding.

Studies on the other less often used techniques have not reached the stage of wide field application.

Numerical modeling has provided guidelines to the field experiments and insights to the theoretical studies of fog conditions.

The laboratory experiments have given the scientists the controlled conditions necessary to validate a number of theories. The unique contribution of chamber tests to a better understanding of the dynamics of fog formation has been widely recognized.⁶

TABLE 8.—SUMMARY OF PRINCIPAL RESEARCH RELATIVE TO WARM FOG DISPERSAL IN THE UNITED STATES, THROUGH 1973¹

[From Moschandreas, 1974]

Area of effort	Year of publication						
	1967 ²	1968	1969	1970	1971	1972	1973
Modeling and numerical experiments.	NWRF	CAL	CAL AFCRL GEOMET	AFCRL MRI NWRF NCAR	CAL MRI GEOMET NWC	CAL AFCRL GEOMET EPRF	AFCRL GEOMET
Field measurements; fog observations.		CAL	CAL MRI EG&G	NCAR AFCRL CAL	CAL MRI	CAL AFCRL FAA NWC	
Chamber tests.		CAL	CAL	USNPGS	CAL	CAL	
Field experiments			CAL MRI EG&G	CAL AFCRL MRI	CAL MRI	AFCRL FAA NWC AFCRL	
Statistical interpretation.							
Model validation.							
Assessment of operational Use.	NWRF		FAA EG&G			AFCRL	AFCRL

¹ Research is listed by agency conducting the research, or sponsoring it, when reporting its contractor's efforts; or by contractor's name when contractor's report is principal reference; individual researchers are not listed because these change, even though the continuity of effort is maintained.

² Work reported prior to 1967 is not included here.

Key: CAL—Cornell Aeronautical Laboratory, Inc.; AFCRL—Air Force Cambridge Research Laboratories; GEOMET—GEOMET, Inc.; MRI—Meteorology Research, Inc.; NWRF—U.S. Navy Weather Research Facility; EPRF—U.S. Navy Environmental Research Facility; EG&G—EG&G Environmental Services Operation; FAA—Federal Aviation Administration; NCAR—National Center for Atmospheric Research; NWC—Naval Weapons Center; USNPGS—U.S. Naval Postgraduate School.

LIGHTNING SUPPRESSION

At any given time over the whole Earth there are about 2,000 thunderstorms in progress, and within these storms about 1,000 cloud-to-ground discharges are produced each second.⁷ Lightning is essentially a long electric spark, believed to be part of the process by which an electric current is conducted from the Earth to the ionosphere, though

⁶ Ibid., pp. 92-93.

⁷ National Science Board, "Patterns and Perspectives in Environmental Science," National Science Foundation, Washington, D.C., 1972, p. 157.

the origin of the lightning discharge is still not fully understood. In fair weather the atmosphere conducts a current from the positively charged ionosphere to the ground, which has a negative charge.

The details of the charge-generating process within a thunderstorm are not well understood, though theories have been proposed by cloud physicists. Probably a number of mechanisms operate together to bring about cloud electrification, though, essentially, the friction of the air on the water droplets and ice crystals in the storm strips off electrons which accumulate near the base of cumulonimbus clouds, while positive charge collects in the upper part. The negative charge near the cloud base induces a local positive charge on the Earth's surface beneath, reversing the normal fair weather situation. When the electrical potential between the cloud and ground becomes sufficiently large, an electrical discharge occurs, in which electrons flow from the cloud to the ground. In addition, there are discharges between clouds and between oppositely charged portions of the same cloud.

In the rapid sequence of events which comprise a lightning stroke, the initial, almost invisible, flow of electrons downward from cloud to Earth, called the leader, is met by an upward-moving current of positive charges, establishing a conducting path of charged particles. A return stroke, much larger, then rushes from the ground to the cloud. All of these events appear as a single flash since they occur in about fifty microseconds; however, while most people perceive the lightning stroke as travelling from cloud to ground, it is actually the return stroke which provides the greatest flash.⁸

In the United States, lightning kills about 200 people annually, a larger toll than that caused by hurricanes. Since 1940, about 7,000 Americans have lost their lives from lightning and related fires.⁹ These casualties occur most often singly or occasionally two at a time, so that they are not nearly so newsworthy as are the multiple deaths and dramatic property damage associated with hurricanes, tornadoes, and floods. On the other hand, a lightning problem affecting large areas is the ignition of forest fires, some 10,000 of which are reported each year in the United States, where the problem is most acute in the Western States and Alaska.¹⁰ Such fires inflict damage on commercial timber, watersheds, scenic beauty, and other resources, causing an estimated annual damage cost of \$100 million.¹¹ Other examples in which lightning can be especially dangerous and damaging include discharges to aircraft and spacecraft and effects on such activities as fuel transfer operations and the handling of explosives.

Because of the relative isolation of personal accidents due to lightning, the only feasible controls over loss of life are through implementation of safety measures which prevent exposure or by protection of relatively small areas and structures with lightning arresters. Forested areas, however, require large area protection from lightning-caused fires in order to promote sound forest management. It is hoped

⁸ Anthes, Richard A., Hans A. Panofsky, John C. Cahlr, and Albert Rango, "The Atmosphere," Columbus, Ohio, Charles E. Merrill, 1975, p. 174.

⁹ U.S. Department of Commerce, "Peak Period for Lightning Nears; NOAA Lists Safety Rules," News Release NOAA 77-156, Washington, D.C., June 19, 1977, p. 1.

¹⁰ Fuquay, Donald M., "Lightning Damage and Lightning Modification Caused by Cloud Seeding," in Wilmut N. Hess (ed.), "Weather and Climate Modification," New York, John Wiley & Sons, 1974, p. 605.

¹¹ *Ibid.*, p. 604.

that the widespread damage to forest resources resulting from the lightning-fire problem can be alleviated through use of weather modification techniques.

Lightning modification

General approaches to lightning suppression through weather modification, which have been contemplated or have been attempted, include:

Dissipation of the cloud system within which the thunderstorm originates or reduction of the convection within the clouds so that vigorous updrafts and downdrafts are suppressed.

Reduction of the number of cloud-to-ground discharges, especially during critical fire periods.

Alteration of the characteristics of discharges which favor forest fuel ignition.

Use of other weather modification techniques to produce rains to extinguish fires or to decrease the probability of ignition through increase of ambient relative humidity and fuel moisture.

Lightning is associated with convective clouds; hence, the most direct suppression method would involve elimination of the clouds themselves or of the convection within them. Removal of the clouds would require changes to gross properties such as temperature instability and moisture content of the air; thus, such modification is not technically, energetically, or economically feasible. However, it might be possible to reduce somewhat the convection within the clouds.¹²

The formation of convective clouds depends on the upward motion of moist air caused by thermal instability and the subsequent production of water through cooling. This condensation releases more heat, which, in turn, causes further buoyancy and rising of the cloud. At these heights the temperature is low enough that the water can freeze, releasing more latent heat and enabling the cloud particles to rise even higher. As a result of the presence of nuclei which are naturally present in the cloud, glaciation proceeds continuously. Through artificial nucleation, by seeding, natural glaciation may be reinforced and development of the cloud assisted. Rapid, premature seeding, however, would still promote buoyancy but could also introduce so much turbulence that the cloud is unable to develop, because colder air entering the cloud by turbulent mixing would lower the changes of the cloud reaching moderate altitudes. Since there is a high correlation between cloud height, convective activity, and lightning, such early nucleation of a cloud should reduce the likelihood of intense electrical activity. Seeding would be accomplished by releasing silver iodide into the cores of growing cumulus clouds; it could be delivered from ground dispensers or from aircraft into the updraft under the cloud base. The amount of seeding material must be chosen carefully, and, in order to increase the chances for cloud dissipation, overseeding is probably most effective, though such overseeding will also tend to reduce precipitation. On the other hand, rainfall may be advantageous for other purposes, including its inhibiting lightning-caused forest fires by providing moisture to the forest fuel. Consequently, the advantages which might be achieved through reducing cloud con-

¹² Stow, C. D., "On the Prevention of Lightning," Bulletin of the American Meteorological Society, vol. 50, No. 7, July 1969, p. 515.

vection and its attendant electrical activity must be weighed against the possible advantages lost through reduced precipitation.¹³

A more efficient lightning-suppression approach might involve interference with the processes which bring about charge separation in the cloud. At least five different mechanisms by which cloud electrification is established have been theorized, and possibly all or most of these mechanisms are active in any given situation, although on different occasions it is likely that some are more effective than others, depending on meteorological conditions and geographical locations.¹⁴ Data are as yet insufficient for determining which mechanisms will predominate. It is not considered likely that a single treatment method would suffice to suppress all lightning activity through prevention of charge buildup, though it is conceivable that a given treatment may be capable of suppressing more than one charge-generating process.¹⁵ In addition to glaciation of the cloud by overseeding (described above in connection with convection reduction), accumulation of charge can be inhibited through seeding with various chemicals which affect the freezing of water. Another technique uses seeding with a conducting chaff (very fine metalized nylon fibers), which increases conductivity between oppositely charged regions of the storm and keeps the electric field from building up to the lightning-discharge level. The chaff fibers are of the type that have been used for radar "jamming," which can be dispensed underneath a thunderstorm from an aircraft. Experiments have shown this attempt at lightning suppression to have some promise.¹⁶

Although reduction in the number of cloud-to-ground discharges through cloud seeding would undoubtedly be instrumental in decreasing the total number of forest fires, ignition is also influenced by such factors as the type of discharge, surface weather conditions, the terrain-fuel complex, and the influence of preceding weather on fuel moisture. The kind of discharge most frequently causing forest fires has been observed and its characteristics have been measured. Observations indicate that ignition is most often caused by hybrid cloud-to-ground discharges having long continuing current phases, whose duration exceeds 40 milliseconds and that the probability of ignition is proportional to the duration of the continuing current phase.¹⁷

Evaluation of lightning suppression technology

Seeding experiments to date have yielded results which suggest that both the characteristics and the frequency of lightning discharges have been modified. The physical processes by which lightning is modified are not understood; however, basic physical charging processes have been altered through massive overseeding with silver iodide freezing nuclei. Direct measurements of lightning electricity have also shown that lightning strokes which contain a long continuing current are probably responsible for most lightning-ignited forest fires. Reduction of the duration of the long continuing current discharge through weather modification techniques may, therefore, be more significant in

¹³ Ibid.

¹⁴ Ibid., pp. 516-519.

¹⁵ Ibid., p. 519.

¹⁶ Kasemir, Heinz W. "Lightning Suppression by Chaff Seeding and Triggered Lightning." In Wilmot N. Hess (editor), "Weather and Climate Modification," New York, Wiley, 1974, N pp. 612-622.

¹⁷ Fuquay, "Lightning Damage and Lightning Modification Caused by Cloud Seeding," 1974, p. 606.

reducing forest fires than reduction of the total amount of lightning produced by storms.

From experiments in lightning suppression carried out under Project Skyfire by the U.S. Forest Service of the Department of Agriculture between 1965-67, Fuquay summarizes the following specific results, based on a total of 26 individual storms (12 seeded and 14 unseeded):¹⁸

Sixty-six percent fewer cloud-to-ground discharges, 50 percent fewer intracloud discharges, and 54 percent less total storm lightning occurred during seeded storms than during the not-seeded storms.

The maximum cloud-to-ground flash rate was less for seeded storms: over a 5-minute interval, the maximum rate averaged 8.8 for not-seeded storms and 5 for seeded storms; for 15-minute intervals, the maximum rate for not-seeded storms averaged 17.7 and 9.1 for seeded storms.

The mean duration of lightning activity for the not-seeded and seeded storms was 101 and 64 minutes, respectively. Lightning duration of the not-seeded storms ranged from 10 to 217 minutes, while that of seeded storms ranged from 21 to 99 minutes.

There was no difference in the average number of return strokes per discrete discharge (4.1 not-seeded versus 4 seeded); however, a significant difference was found for hybrid discharges (5.6 not-seeded versus 3.8 seeded).

The average duration of discrete discharges (period between first and last return stroke) decreased from 235 milliseconds for not seeded storms to 182 milliseconds for seeded storms.

The average duration of continuing current in hybrid discharges decreased from 187 milliseconds for not-seeded storms to 115 milliseconds for seeded storms.

In a recent Federal appraisal of weather modification technology it was concluded that results of field experiments to suppress lightning through silver iodide seeding have been ambiguous.¹⁹ Although analysis of data previously obtained is continuing, the experimental seeding program of the Forest Service has been terminated. In more recent experiments, thunderstorms have been seeded from below with chaff (very fine metalized nylon fibers). Based on an analysis of 10 chaff-seeded thunderstorms and 18 unseeded control storms, the number of lightning occurrences during the seeded storms was about 25 percent of those observed in the control storms. This observed difference was statistically significant even though the experiments were not strictly randomized.²⁰

Experiments in lightning modification through cloud seeding have given results showing that, in some cases, lightning can be modified in a beneficial manner. From these results and the measured characteristics of lightning strokes, a hypothesis of lightning modification is being developed. There has been progress in identifying significant correlations between occurrence of lightning and such variables as storm

¹⁸ Fuquay, "Lightning Damage and Lightning Modification Caused by Cloud Seeding," 1974, p. 611.

¹⁹ U.S. Domestic Council, Environmental Resources Committee, Subcommittee on Climate Change, "The Federal Role in Weather Modification," Washington, D.C., December 1975, p. 10.

²⁰ Ibid.

size, updraft characteristics, precipitation rates, and hail occurrence. According to Fuquay, such early successes ought not obscure the magnitude of the research yet required in order to identify and quantify the degree and applicability of lightning modification to the lightning-fire problem.²¹ He also warns that:

Until more is known about the adverse effects of seeding incipient thunderstorms, unexpected and adverse effects must be considered, although improved numerical models that accurately predict cloud development and the effects of seeding should minimize the risk of unexpected events.²²

MODIFICATION OF SEVERE STORMS

Severe storms have a greater immediate impact on human life and property than most other weather phenomena. A major portion of losses due to natural disasters results from two of the most destructive kinds of severe storms—hurricanes and tornadoes. During an average year the U.S. mainland is threatened by 8 tropical storms and experiences over 600 tornadoes.²³ Among the results of the annual devastation from these storms are the loss of hundreds of lives and the accumulation of hundreds of millions of dollars in property damage.

Perhaps the most important problems to be attacked in weather modification are associated with the abatement of severe storms. While rainfall augmentation promises borderline economic value at best, alternatives which can contribute more significantly to severe water shortages may prove more suitable. On the other hand, the annual threat of tolls in damages and fatalities from hurricanes and tornadoes will persist year after year, and research directed toward modification of these severe phenomena requires continued support. There have been dramatic attempts, with some successes, in demonstrating the potential reduction of the hazards of hurricanes; however, almost no research has been directed toward tornado suppression.

Hurricanes

A hurricane is an intense cyclone which forms over tropical seas, smaller in size than middle-latitude cyclones, but much larger than a tornado or a thunderstorm. With an average size of 500 miles (800 kilometers) in diameter, the hurricane consists of a doughnut-shaped ring of strong winds in excess of 64 knots which surrounds an area of extremely low pressure and calm at the storm's center, called the eye.²⁴ The generic name for all vortical circulations originating over tropical waters is "tropical cyclone." When fully developed with sufficiently strong winds, such storms are called hurricanes in the Atlantic and the eastern Pacific Oceans, typhoons in the northwest Pacific, baguios in the Philippines, Bengal cyclones in the Indian Ocean, and willy-willies near Australia. For a tropic cyclone whose winds are in the range of 33 to 64 knots, the official name in the United States is a tropical storm. The hurricane season is that portion of the year having a relatively

²¹ Fuquay, "Lightning Damage and Lightning Modification Caused by Cloud Seeding," 1974, p. 612.

²² *Ibid.*, p. 606.

²³ Federal Coordinator for Meteorological Services and Supporting Research, "Federal Plan for Meteorological Services and Supporting Research: Fiscal Year 1973," U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C., January 1972, p. 1.

²⁴ Anthes, Richard A., Hans A. Panofsky, John J. Cahir, and Albert Rango. "The Atmosphere." Columbus, Ohio, Charles E. Merrill, 1975, p. 150.

high incidence of hurricanes and usually is regarded as the period between June and November in the Northern Hemisphere.²⁵

Owing to their duration, which exceeds that of earthquakes, and to their violence, which approaches that of tornadoes, hurricanes are the most destructive natural phenomena. Prior to Hurricane Agnes in 1972, whose total damage exceeded \$3 billion, the annual hurricane property losses in the United States amounted to about \$450 million, although two hurricanes in the 1960's, Betsy (1965) and Camille (1969), each caused damage exceeding \$1.4 billion.²⁶ Improved techniques in hurricane detection and warning have dramatically reduced the number of deaths caused by hurricanes; however, property losses have continued to grow, as a result of increased population and activities in vulnerable coastal areas, with the attendant concentration of new houses, buildings, and other facilities of higher replacement value. Figure 8 shows the simultaneous increase in property losses and decrease in deaths due to hurricanes in the United States in the 20th century through 1969.

Devastation and fatalities occur essentially from three phenomena associated with hurricanes: the force of the winds in the storm itself, the storm surge on coastal areas, and flooding which can result from excessive and widespread rainfall as the storm moves inland. Since wind force varies with the square of the wind speed, a 50-mile-per-hour wind exerts four times as much force as a 25-mile-per-hour wind. Accordingly, a 10-percent reduction in maximum windspeed yields a decrease in wind force of about 20 percent.²⁷ Attempts to modify hurricane winds can thus be expected to reduce storm damage caused by winds in approximate proportion to the corresponding reduction in wind force.

²⁵ Federal Coordinator for Meteorological Services and Supporting Research, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, "National Hurricane Operations Plan," FCM 77-2, Washington, D.C., May 1977, pp. 6-7.

²⁶ Gentry, R. Cecil, "Hurricane Modification," In Wilmot N. Hess (ed.). "Weather and Climate Modification," New York, John Wiley & Sons, 1974, p. 497.

²⁷ *Ibid.*, p. 498.

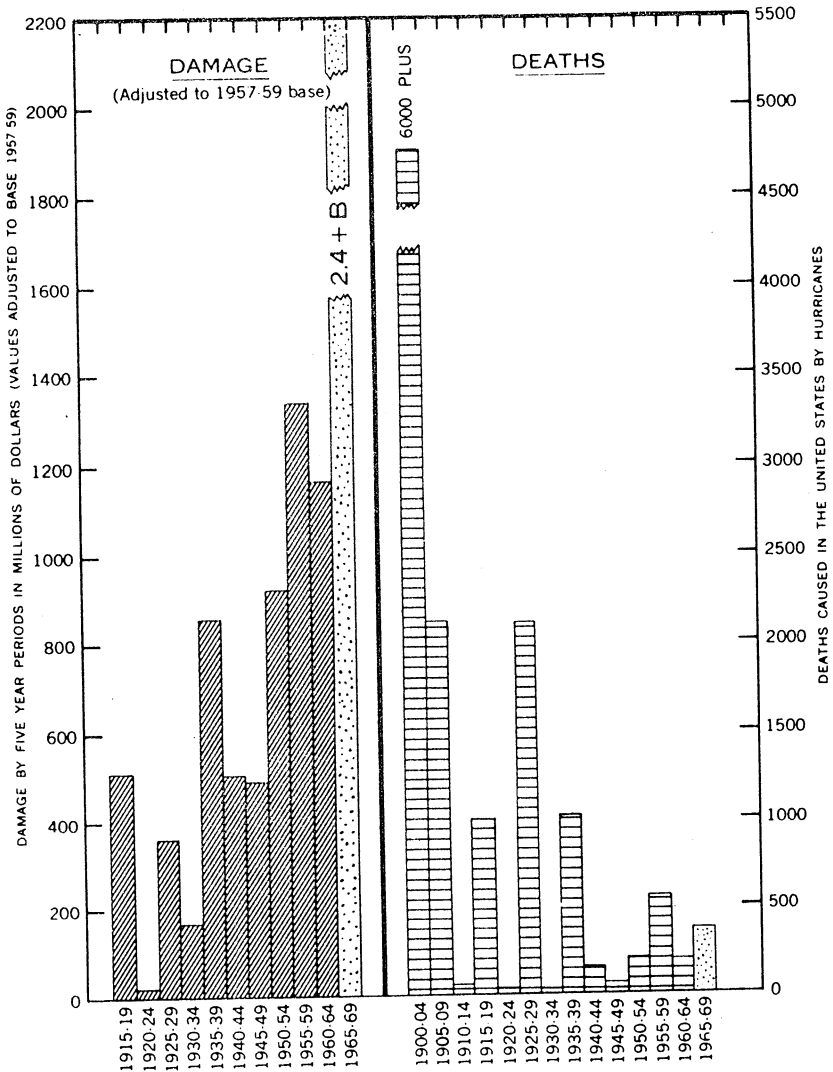


FIGURE 8.—Losses in the United States from hurricanes, 1915 through 1969, in 5-year periods (from National Oceanic and Atmospheric Administration).

As a hurricane moves across the coast from the sea, the strong winds pile up water to extreme heights, causing storm surges. The resulting onrushing water wreaks damage to shoreline and coastal structures. The severity of the storm surge is increased by the hurricane-generated wind waves which are superimposed on the surge. From Hurricane Camille, the storm surge at Pass Christian, Miss., was 24.6 feet, higher than any previous recorded tide. As a result, 135 people were killed, 63,000 families suffered personal losses, and Mississippi alone sustained \$1 billion in damage.²⁸ The height of the storm surge depends both on

²⁸ Anthes, Panofsky, Cahir, and Rango, "The Atmosphere," 1975, p. 159.

the windspeed and the shape and slope of the sea bottom offshore. If there is a sharp dropoff in depth not far off the beach, the rise of the sea level will be small, for example. Nearshore attempts to modify a hurricane could lead to uncertain results, depending upon local conditions. If the windspeed is reduced without moving the position of maximum winds along the coast, the overall effect would likely be a reduction in storm surge. However, should the modification activity result in developing a new windspeed maximum at a different location, the surge might increase or decrease, depending on bathymetry and bottom topography.²⁹ Solutions are not yet clear, and the storm surge prediction problem is being studied intensely with the use of numerical models.

Major hurricane damage can often be attributed to heavy rains and the massive and sudden flooding which can result as the storm moves inland. In mountainous regions especially, the floods from such rainfall can be devastating in losses to both life and property. Such flooding was a major contributor to the 118 deaths and \$3.5 billion in property destruction³⁰ which resulted in June 1972 from Hurricane Agnes, which set the record of achieving the greatest damage toll of all U.S. hurricanes. Ironically, Agnes caused almost no major damage as it went ashore. Hurricane modification activities which have been attempted or are contemplated are unfortunately not designed to reduce the rains significantly, but are intended rather to reduce the maximum winds.³¹

Generation and characteristics of hurricanes

A hurricane can be thought of as a simple heat engine driven by temperature differences between the center of the storm and its margins. At each level the central column must be warmer than the surrounding area to insure maintenance of the strong convection on which the storm depends.³² While the energy which forms extratropical cyclones is provided by temperature differences between different air masses, the energy which generates and maintains hurricanes and other tropical cyclones is derived from a single air mass through condensation of water vapor, and there are seldom present any of the frontal activities which are characteristic of storms originating in temperate latitudes. The moisture-laden winds continuously supply water vapor to the tropical storm, and the condensation of each gram of the vapor releases about 580 calories of latent heat. Within this thermally driven heat engine tremendous quantities of energy are converted from heat to mechanical motion in a short time, a fact readily apparent from the fury of the winds. The daily power of the energy liberated within a hurricane has been estimated to be about ten thousand times the daily power consumption in the United States.³³ The importance of the ocean in providing moisture to a hurricane is seen in the weakening and dissipation of the storms after they have crossed coastlines and travel over land.

²⁹ Gentry, "Hurricane Modification," 1974, p. 499.

³⁰ National Advisory Committee on Oceans and Atmosphere, "The Agnes Floods: a Cost-Audit of the Effectiveness of the Storm and Flood Warning System of the National Oceanic and Atmospheric Administration," a report for the Administrator of NOAA. Washington, D.C., Nov. 22, 1972, p. 1.

³¹ Gentry, "Hurricane-Modification," 1974, p. 499.

³² Donn, William L. "Meteorology." 4th edition. New York, McGraw-Hill, 1975, p. 336.

³³ Ibid., p. 338.

Exactly how hurricanes form is not yet fully understood. They are all generated in the doldrums (a region of equatorial calms), though rarely if ever within latitudes closer than 5 degrees from the Equator, over water whose temperature is at least 27° C. The relatively high surface temperature is necessary for initiation of the convection. Hurricanes are relatively rare features even of the tropics, and the exact triggering mechanism is not yet known.³⁴ Their origin is usually traced to a low pressure disturbance which originates on the equatorial side of the trough of an easterly wave.

Such a tropical disturbance moves slowly westward and slightly poleward under the direction of the tropical east winds. If conditions are right, this cluster of thunderstorms intensifies as it reaches the region near the boundary between the tropical easterlies and the middle-latitude westerlies, at about 25° latitude. It may then follow a path which reverses toward the east as it leaves the tropics. The tracks of 13 major hurricanes in the Northwest Atlantic Ocean are shown in figure 9.

The development of the intense storm which might result from the conditions noted above is described in the following way by Anthes et al.:

The increased inflow toward the center of falling pressure produces increased lifting of air, so that the thunderstorms become more numerous and intense. The feedback cycle is now established. The inflowing air fuels more intense thunderstorm convection, which gradually warms and moistens the environment. The warmer air in the disturbance weighs less, and so the surface pressure continues to fall. The farther the pressure falls, the greater the inflow and the stronger the convection. The limit to this process would occur when the environment is completely saturated by cumulonimbus clouds. Further condensation heating would not result in additional warming, because the heat released would exactly compensate for the cooling due to the upward expansion of the rising air.³⁵

³⁴ Ibid.

³⁵ Anthes, Panofsky, Cahir, and Rango, "The Atmosphere," 1975, p. 154.

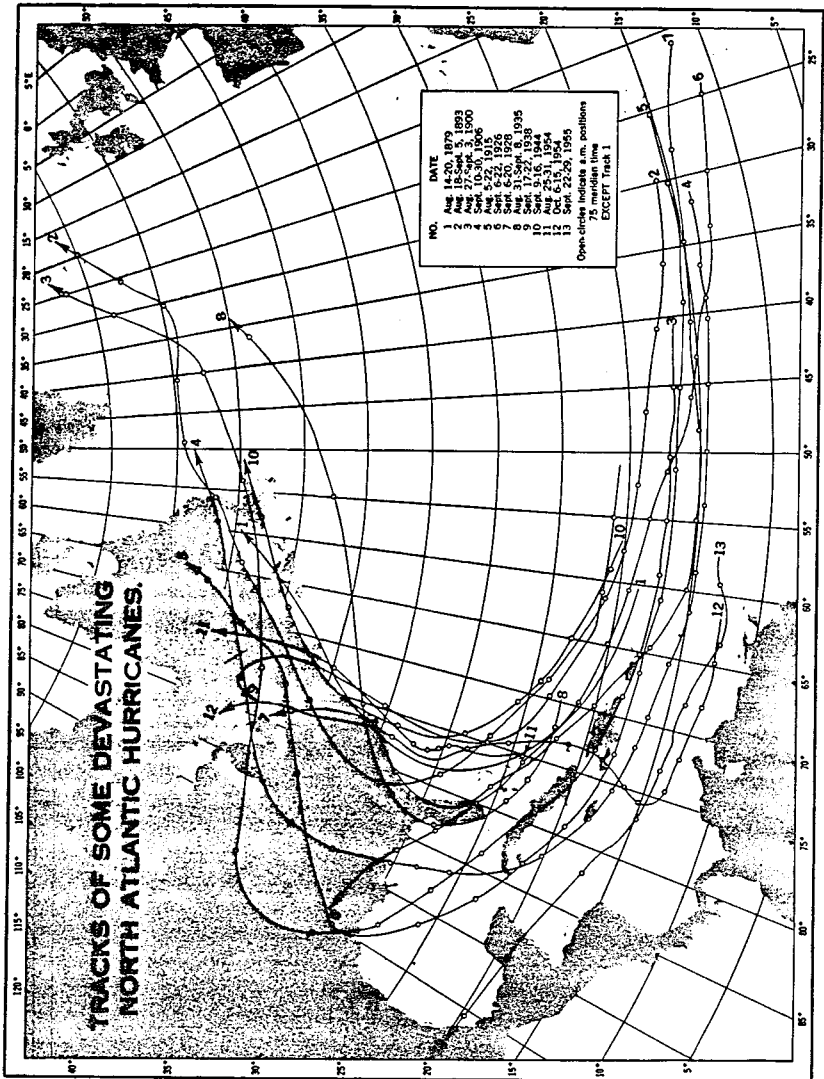


FIGURE 9.—Tracks of thirteen major hurricanes in the North Atlantic from 1879 through 1955 (from U.S. Naval Oceanographic Office, Publication No. 21, Sailing Directions for the West Indies, 1958).

As the storm forms, the winds begin to strengthen about the center, increasing especially to the right of the direction in which the center is moving, normally on the poleward side. The clouds organize themselves into a system and dense cirrus move forward in the direction of the movement of the center. Suddenly, the pressure falls over a small area and hurricane force winds form a tight band of 20 to 40

miles radius around the center. The well-organized clouds show a spiraling structure, and the storm acquires an eye, a small nearly circular area, coinciding with the region of lowest pressure. The winds in the eye are light and variable and the clouds are scattered or entirely absent.³⁶ As the storm matures, the pressure ceases to fall and the maximum winds do not increase further. Now the storm expands horizontally and large amounts of air are drawn in. As the storm expands to a radius of about 200 miles or more it becomes less symmetrical. Figure 10 is a vertical cross-section of the structure of a typical mature hurricane, showing the direction of flow and cloud distribution.³⁷

In spite of the great damage and fatalities caused by hurricanes, their effects are not completely destructive. In many areas of Southeast Asia and the west coast of Mexico, tropical storms are depended upon for a large part of the water supply. Throughout the Southern United States, hurricanes have also provided valuable drought relief.³⁸ Hurricane and other tropical cyclones are always characterized by high wind velocities and by torrential rains. Wind velocities of 60 to 70 knots and more are normal for such storms. The air rotates rapidly, moving spirally toward the center. Maximum gusts exceed 100 knots and may reach 200 knots, although such high speeds are unrecorded since instruments are blown away or made inoperable at these wind speeds.³⁹

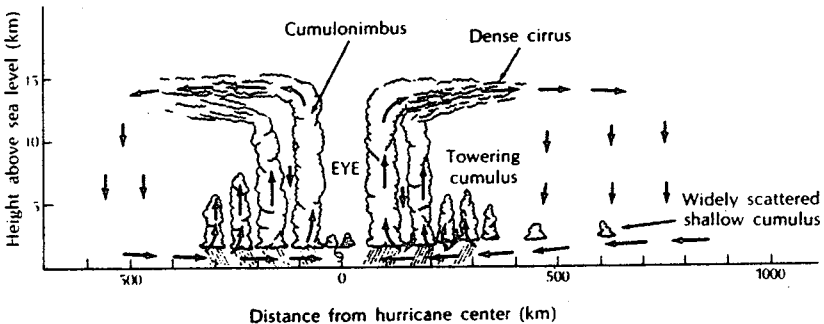


FIGURE 10.—Vertical cross section through a hurricane, showing typical cloud distribution and direction of flow, as functions of height and distance from the eye. (From Anthes, Panofsky, Cahir, and Rango, 1975.)

Compared with extratropical storms, hurricanes are generally small, circularly shaped zones of intense low pressure, with very steep pressure gradients between the center and the periphery. The pressure drop between the eye and the periphery is quite large, 20 to 70 millibars being typical. The winds are in a constant circular cyclonic motion (counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere); however, the center of the storm is a

³⁶ Petterssen, Sverre, "Introduction to Meteorology," second edition, New York, McGraw-Hill, 1958, pp. 242-243.

³⁷ Anthes, Panofsky, Cahir, and Rango, "The Atmosphere," 1975, p. 157.

³⁸ Rehl, Herbert, "Introduction to the Atmosphere," New York, McGraw-Hill, 1965, pp. 178-179.

³⁹ Gentill, J., "Tropical Cyclones." In Rhodes W. Fairbridge (ed.), "The Encyclopedia of Atmospheric Sciences and Astrogeology," Reinhold, New York, 1967, p. 1028.

calm region of low pressure, called the eye, which is about 10 miles across on the average. The warm dry character of this region is due to subsiding air, which is necessary for existence of the storm. Around the eye is the wall, consisting of cumulonimbus clouds and the attendant extreme instability and rising motion; in the wall area adjacent to the eye, heavy rains fall. Out from the central zone altostratus and nimbostratus clouds mix to form a layer with a radius as great as 200 miles. At higher altitudes and reaching to the outer regions of the storm is a mixture of cirrus and cirrostratus clouds.⁴⁰

In a mature hurricane a state of relative equilibrium is reached eventually, with a particular distribution of wind, temperature, and pressure. Such distributions for a typical hurricane are shown schematically in figure 11. Note that the greatest pressure change and the maximum windspeeds are in the region of the wall clouds, near the center of the storm.⁴¹

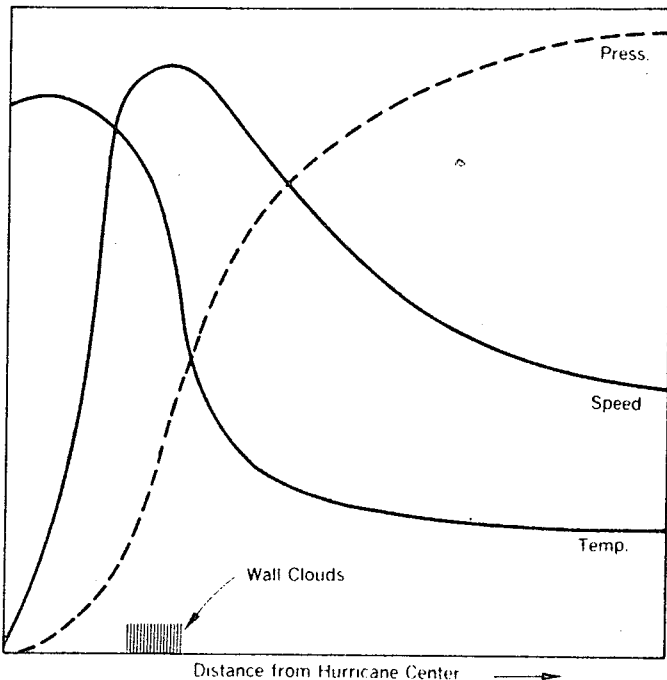


FIGURE 11.—Radial profiles of temperature, pressure, and windspeed for a mature hurricane. The temperature profile applies to levels of 3 to 14 kilometers; pressure and windspeed profiles apply to levels near the surface. (From Gentry, 1974.)

Modification of hurricanes

Since the damage inflicted by hurricanes is primarily a result of the high windspeeds, the principal goal of beneficial hurricane modifica-

⁴⁰ Jerome Williams, John J. Higginson, and John D. Rohrbough. "Sea and Air: The Naval Environment," Annapolis, Md.: U.S. Naval Institute, 1968, pp. 262-263.

⁴¹ Gentry, "Hurricane Modification," 1974, pp. 502-503.

tion is the reduction of the severity of the storm's maximum winds. The winds result from the pressure distribution, which, in turn, is dependent on the temperature distribution. Thus, hurricane winds might be reduced through reduction of temperature contrasts between the core of the storm and the region outside.

Gentry notes that there are at least two important fundamentals of hurricanes which have been established through recent studies, which suggest possible approaches to modification of the severity of the storms:⁴²

The transfer of sensible and latent heat from the sea surface to the air inside the storm is necessary if the hurricane is to reach or retain even moderate intensity.

The energy for the entire synoptic-scale hurricane is released by moist convection in highly organized convective-scale circulations located in and around the eye of the storm and in the major rain bands. The first principle accounts for the fact that hurricanes form only over warm tropical waters and begin to dissipate after moving over land or cool water, since neither can provide sufficient energy flow to the atmosphere to maintain the intensity of the storm. The second principle explains why such a low percentage of tropical disturbances grow to hurricane intensity. Possible field experiments for beneficial modification of hurricanes follow from these principles. On the basis of the first, techniques for inhibiting evaporation might be employed to reduce energy flux from the sea surface to the atmosphere. Based on the second principle, it might be possible to affect the rate of release of latent heat in that small portion of the total storm which is occupied by the active convective-scale motions in such a way that the storm is weakened through redistribution of heating.⁴³

Gentry discusses a number of possible mechanisms which have been suggested for bringing about changes to the temperature field in a hurricane.⁴⁴ Since the warm core development is strongly influenced by the quantity of latent heat available for release in air columns rising near the center of the storm, the temperature might be decreased through reducing the water vapor in these columns, the water vapor originating through evaporation from the sea surface inside the region of high storm winds. It has been suggested that a film spread over the ocean would thus reduce such evaporation. No such film is available, however, which could serve this purpose and withstand rupturing and disintegration by the winds and waves of the storm. Another suggestion, that the cooling of the sea surface might be achieved through dropping cold material from ships or aircraft, is impractical, since such great expenditure of energy is required. It has also been postulated that the radiation mechanisms near the top of the hurricane might be modified through distribution of materials of various radiation properties at selected locations in the clouds, thus inducing changes to the temperatures in the upper part of the storm. This latter suggestion needs further evaluation both from the standpoint of its practicality and from the effect such a change, if included, would theoretically have on storm intensity.

The potential schemes for hurricane modification which seem to be practical logistically and offer some hope for success involve attempts

⁴² *Ibid.*, 1974, p. 503.

⁴³ *Ibid.*, p. 504.

⁴⁴ *Ibid.*, p. 505.

to modify the mechanism by which the convective processes in the eye wall and the rain bands distribute heat through the storm. Since water vapor is condensed and latent heat released in the convective clouds, it should be possible to influence the heat distribution in the storm through changing the pattern of these clouds.⁴⁵ Recent success in modifying cumulus clouds promises some hope of success in hurricane modification through cloud seeding. By modifying the clouds in a hurricane, the storm itself may be modified, since the storm's intensity will be affected through changing the interactions between the convective (cloud) scale and the synoptic (hurricane) scales.⁴⁶ Figure 12 shows how the properties of a hurricane might be redistributed as a result of changing the temperature structure through seeding the cumulus cloud structure outside the wall. The solid curves in the figure represent distributions of temperature, pressure, and windspeed identical with those shown in figure 11 without seeding; the dashed curves represent these properties as modified through seeding.⁴⁷

The first attempt at hurricane modification was undertaken by scientists of the General Electric Co., on a hurricane east of Jacksonville, Fla., on October 13, 1947. Clouds outside of the wall were seeded with dry ice in order to cause freezing of supercooled water, so that the accompanying release of latent heat might alter the storm in some manner. Results of the experiment could not be evaluated, however, owing to the lack of adequate measuring equipment for recording cloud characteristics. Furthermore, the penetration of the wall clouds to the eye or to the area of intense convection in the storm's rain bands was prevented by failure of navigation aids. Based on information acquired from more recent seeding experiments and increased understanding of hurricanes, it seems doubtful that the 1947 seeding could have been effective.⁴⁸

⁴⁵ *Ibid.*

⁴⁶ *Ibid.*, p. 504.

⁴⁷ *Ibid.*, pp. 504-505.

⁴⁸ *Ibid.*, pp. 505-506.

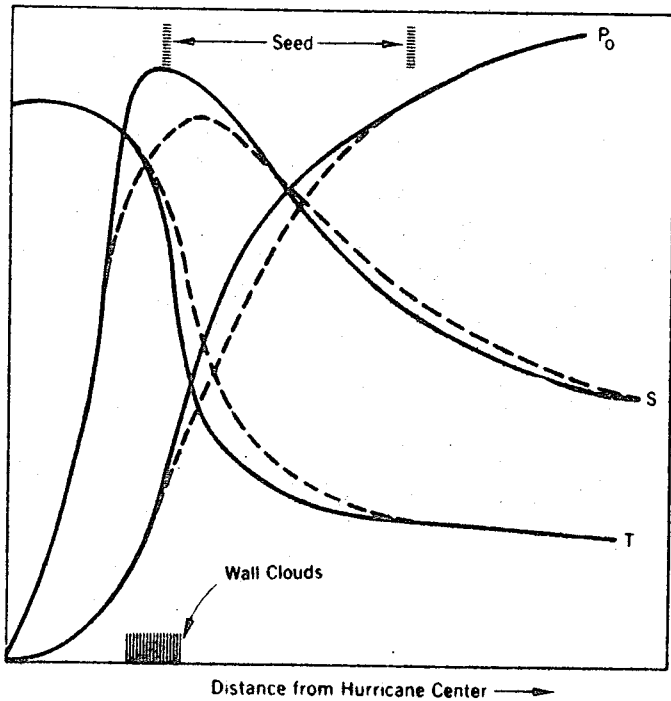


FIGURE 12.—Radial profiles of temperature, pressure, and windspeed for a mature hurricane before (solid curves) and possible changes after (dashed curves) seeding. (The solid curves are the same as those in fig. 11.) (From Gentry, 1974.)

Hurricane seeding experiments were undertaken by the Department of Commerce and other agencies of the Federal Government in 1961, initiating what came to be called Project Stormfury. To date only four hurricanes have actually been seeded under this project—all of them between 1961 and 1971; however, Stormfury has also included investigation of fundamental properties of hurricanes and their possible modification through computer modeling studies, through careful measurements of hurricane properties with research probes, and through improvements in seeding capabilities.

The goal of hurricane seeding is the reduction of the maximum winds through dispersing the energy normally concentrated in the relatively small band around the center of the storm. The basic rationale for seeding a hurricane with silver iodide is to release latent heat through seeding the clouds in the eye wall, thus attempting to change the temperature distribution and consequently weaken the sea level pressure gradient. It is assumed that the weakened pressure gradient will allow outward expansion, with the result that the belt of maximum winds will migrate away from the center of the storm and will therefore weaken. Actually, stimulation of condensation releases much more latent heat than first hypothesized in 1961, and theoretical hurricane models show that a new eye wall of greater diameter can be developed by encouraging growth of cumulus clouds through dynamic seeding.⁴⁹

⁴⁹ Ibid., pp. 510–511.

Following seeding of the four storms in Project Stormfury, changes were perceived, but all such changes fell within the range of natural variability expected of hurricanes. In no case, however, did a seeded storm appear to increase in strength. Hurricane Debbie, seeded first on August 18, 1969, exhibited changes, however, which are rarely observed in unseeded storms. Maximum winds decreased by about 30 percent, and radar showed that the eye wall had expanded to a larger diameter shortly after seeding. After Debbie had regained her strength on August 19, she was seeded again on August 20, following which her maximum winds decreased by about 15 percent.⁵⁰ Unfortunately, data are not adequate to determine conclusively that changes induced in Debbie resulted from seeding or from natural forces. Observations from Hurricane Debbie are partially supported by results from simulated experiments with a theoretical hurricane model; however, simulation of modification experiments with other theoretical models have yielded contrary results.⁵¹

One of the problems in evaluating the results of hurricane modification is related to the low frequency of occurrence of hurricanes suitable for seeding experiments and the consequent small number of such experiments upon which conclusions can be based. This fact requires that hurricane seeding experiments must be even more carefully planned, and monitoring measurements must be very comprehensive, so that data acquired in the few relatively large and expensive experiments can be put to maximum use. Meanwhile theoretical models must be improved in order to show the sensitivity of hurricane characteristics to changes which might be induced through seeding experiments.

Gentry has suggested that the following future activities should be conducted under Stormfury:⁵²

1. Increased efforts to improve theoretical models.
2. Collection of data to further identify natural variability in hurricanes.
3. Expanded research—both theoretical and experimental—on physics of hurricane clouds and interactions between the cloud and hurricane scales of motion.
4. More field experiments on tropical cyclones at every opportunity.
5. Tests of other methods and material for seeding.
6. Further evaluation of other hypotheses for modifying hurricanes.
7. Development of the best procedures to maximize results of field experiments.

Tornadoes

The structure of tornadoes is similar to that of hurricanes, consisting of strong cyclonic winds⁵³ blowing around a very low pressure center. The size of a tornado, however, is much smaller than that of a hurricane, and its wind force is often greater. The diameter of a tor-

⁵⁰ National Oceanic and Atmospheric Administration, "Stormfury—1977 to Seed One Atlantic Hurricane," U.S. Department of Commerce News, NOAA 77-248, Washington, D.C., Sept. 20, 1977, p. 3.

⁵¹ Gentry, "Hurricane Modification," 1974, p. 517.

⁵² *Ibid.*, p. 519.

⁵³ Cyclonic winds blow counterclockwise around a low pressure center in the Northern Hemisphere; in the Southern Hemisphere they blow clockwise.

nado is about one-fourth of a kilometer, and its maximum winds can exceed 250 knots in extreme cases.⁵⁴ On a local scale, the tornado is the most destructive of all atmospheric phenomena. They are extremely variable, and their short lifetime and small size make them nearly impossible to forecast with any precision.

Tornadoes occur in various parts of the world; however, in the United States both the greatest number and the most severe tornadoes are produced. In 1976, there were reported 832 tornadoes in this country,⁵⁵ where their origin can be traced to severe thunderstorms, formed when warm, moisture-laden air sweeping in from the Gulf of Mexico or the eastern Pacific strikes cooler air fronts over the land. Some of these thunderstorms are characterised by the violent updrafts and strong tangential winds which spawn tornadoes, although the details of tornado generation are still not fully understood. Tornadoes are most prevalent in the spring and occur over much of the Eastern two-thirds of the United States; the highest frequency and greatest devastation are experienced in the States of the middle South and middle West. Figure 13 shows the distribution of 71,206 tornadoes which touched the ground in the contiguous United States over a 40-year period.

Even in regions of the world favorable to severe thunderstorms, the vast majority of such storms do not spawn tornadoes. Furthermore, relatively few tornadoes are actually responsible for deaths and severe property damage. Between 1960 and 1970, 85 percent of tornado fatalities were caused by only 1 to 1½ percent of reported tornadoes.⁵⁶ Nevertheless, during the past 20 years an average of 113 persons have been killed annually by tornadoes in the United States, and the annual property damage from these storms has been about \$75 million.⁵⁷

Modification of tornadoes

Alleviation from the devastations caused by tornadoes through weather modification techniques has been a matter of considerable interest. As with hurricanes, any such modification must be through some kind of triggering mechanism, since the amount of energy present in the thunderstorms which generate tornadoes is quite large. The rate of energy production in a severe thunderstorm is roughly equal to the total power-generating capacity in the United States in 1970.⁵⁸ The triggering mechanism must be directed at modifying the circulation through injection of small quantities of energy.

⁵⁴ Anthes, Panofsky, Cahir, and Rango, "The Atmosphere," pp. 150, 180.

⁵⁵ NOAA news. "Skywarn 1977—Defense Against Tornadoes," U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Rockville, Md., Feb. 18, 1977, vol. 2, No. 4, pp. 4-5.

⁵⁶ Davies-Jones, Robert and Edwin Kessler, "Tornadoes." In Wilmot N. Hess (ed.), "Weather and Climate Modification," New York, John Wiley & Sons, 1974, p. 552.

⁵⁷ Ibid.

⁵⁸ Anthes, Panofsky, Cahir, and Rango, "The Atmosphere," 1975, p. 185.

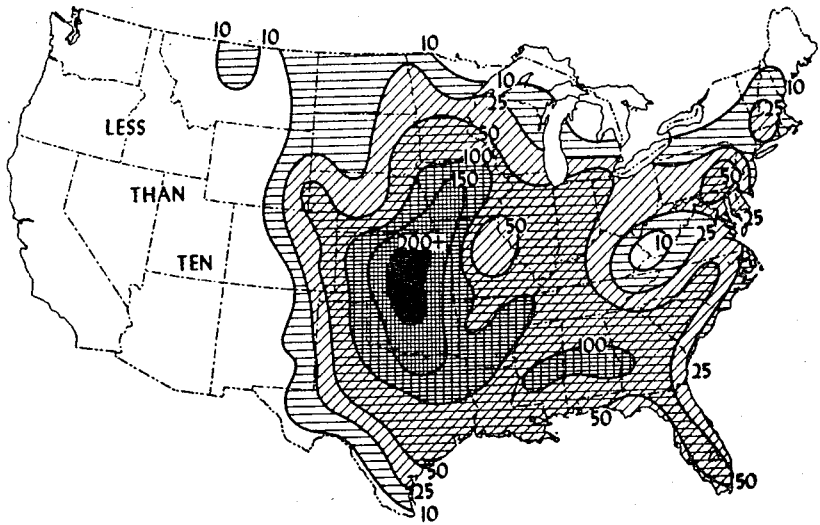


FIGURE 13.—Tornado distribution in the United States, where contours enclose areas receiving equal numbers of tornadoes over a 40-year period. Frequencies are based on number of 2-degree squares experiencing first point of contact with the ground for 71,206 tornadoes. (From Wilkins, 1967, in *Encyclopedia of Atmospheric Sciences and Astrology*, Reinhold.)

Tornado modification has not been attempted in view of the present insufficient knowledge about their nature and the lack of adequate data on associated windspeeds. There are potential possibilities, however, which can be considered for future research in tornado modification. One proposal is to trigger competing meteorological events at strategic locations in order to deprive a tornadic storm of needed inflow. This technique, suggested by the presence of cumulus clouds over forest fires, volcanoes, and atomic bomb blasts could use arrays of large jet engines or oil burning devices. Another approach for dispersal of convective clouds which give rise to thunderstorms might involve the use of downrush created by flying jet aircraft through the clouds. A further possibility would depend on changing the characteristics of the Earth's surface such as the albedo or the availability of water for evaporation.⁵⁹

Tornadoes tend to weaken over rougher surfaces due to reduction of net low-level inflow. Upon meeting a cliff, tornadoes and waterspouts often retreat into the clouds, and buildings also tend to reduce ground level damage. Thus, forests or artificial mounds or ridges might offer some protection from tornadoes, although very severe tornadoes have even left swaths of uprooted trees behind.⁶⁰

Modification of tornadoes by cloud seeding would likely be the cheapest and easiest method. Sodium iodide seeding could possibly shorten the life of a tornado if the storm's cold air outflow became stronger and overtook the vortex sooner, thus cutting off the inflow. Seeding a neighboring cell upstream of the low-level inflow might also be bene-

⁵⁹ Davies-Jones and Kessler, "Tornadoes," 1974, p. 590.

⁶⁰ *Ibid.*

ficial, if the rapidly developing seeded cloud, competing for warm, moist air, reduces the inflow and weakens the rotating updraft. It is also possible that seeding would increase low-level convergence, leading to intensification of a tornado.⁶¹

Davies-Jones and Kessler conclude that:

Any efforts to modify a severe storm with potential or actual tornadoes obviously will have to be carried out with extreme caution * * *. Actual modification attempts on menacing tornadoes are probably several years away. In the meantime, we should seek improved building codes and construction practices and continue research into the actual morphology of convective vortices.⁶²

In spite of the speculations on how tornadoes might be modified, no tests have yet been conducted. The small size and brief lifetime of tornadoes make them difficult and expensive to investigate. However, in view of their destructiveness, they must be given more attention by meteorologists, who should seek ways to mitigate their effects. Only further research into the character of tornadoes, followed by careful investigation of means of suppressing them, can lead to this desired reduction in the effects of tornadoes.

TECHNICAL PROBLEM AREAS IN PLANNED WEATHER MODIFICATION

In this section a number of major problem areas associated with the development of weather modification technology will be addressed. These topics are not necessarily confined to the modification of any one of the weather phenomena discussed in the previous section but apply in general to a number of these categories of phenomena. Some of the problem areas have implications which extend beyond the purely technical aspects of planned weather modification, bearing also on social, economic, and legal aspects as well. Included are discussions on the problems of seeding technology, evaluation of results of weather modification projects, extended area and extended time effects from inadvertent weather modification, and potential approaches to weather and climate modification which involve techniques other than seeding. The problems of inadvertent weather modification and of potential ecological effects from planned weather modification could also properly be included in this section; however, these topics are addressed in chapter 4 and 13, respectively, in view of their special significance.

SEEDING TECHNOLOGY

In recent years there has been progress in developing a variety of ice-nucleating agents available for cloud seeding, although silver iodide continues to be the principal material used. Other seeding agents which have been studied include lead iodide, metaldehyde, urea, and copper sulfide. Nucleants have been dispensed into the clouds from both ground-based generators or from aircraft. In some foreign countries, such as the Soviet Union, rockets or artillery have been used to place the seeding material into selected regions of the clouds; however, this means of delivery does not seem to be acceptable in the United States.

There have been both difficulties and conflicting claims regarding the targeting of seeding materials, particularly from ground generators, ever since the earliest days of cloud seeding. It is always hoped that

⁶¹ Ibid., pp. 590-591.

⁶² Ibid., p. 591.

the nucleant will be transported from the generator site by advection, convection, and diffusion to parts of the clouds which have been identified for modification. Difficulties have been observed under unstable conditions, where the plume of nucleants was disrupted and wide angle turbulent diffusion was severe. Valley locations in mountainous areas are often subjected also to inversions and to local channeling so that trajectory determinations are extremely difficult. Even plumes of seeding material from aircraft have shown an erratic pattern. The problems of irregular plume geometry appear to increase as distortion occurs near fronts in mountain terrain, that is, under just the circumstances where cloud seeding is often attempted.⁶³

In view of the limited vertical transport of silver iodide observed in some studies (that is, up to 450 meters above the terrain at distances of several kilometers from the generators), some have concluded that, under conditions of the tests, ground-based generators are probably not effective. However, other studies have shown that one cannot generalize that ground generators are not always effective. Thus, more desirable effects can be achieved with generators at high altitudes where there is little chance of inversion trapping of the silver iodide as in other tests.⁶⁴

Much of the ambiguity associated with ground-based generators is reduced when the nucleant material is placed into the cloud directly by an aircraft using flares or rockets. However, airborne seeding also presents important targeting problems. Of course, targeting difficulties are reduced in the case of single cloud seeding, where the aircraft is flying directly beneath the cloud in the active updraft area. However, questions of proper vertical ascent persist when the objective is to lay down from the aircraft an elevated layer of nucleant-rich air that is intended to drift over the target area.⁶⁵

In conclusion, the 1973 National Academy of Sciences study says:

To summarize the results of the past few years' work on targeting, it can be said that earlier doubts about the inevitability of nuclei reaching effective altitudes from ground generators tend to be supported by a number of recent observational studies. Some of these merely confirm the rather obvious prediction that stable lapse rates will be unfavorable to the efficacy of ground generators; others indicate surprising lack of vertical ascent under conditions that one might have expected to favor substantial vertical transport. The recent work also tends to support the view that plumes from ground generators in mountainous terrain must be expected to exhibit exceedingly complex behavior; and each site must be expected to have its own peculiarities with respect to plume transport. Tracking experiments become an almost indispensable feature of seeding trials or operations in such cases.⁶⁶

There are three types of airborne seeding agent delivery systems in common use—burners, flares, and hoppers. Burners are used mainly for horizontal seeding, often at the cloud base as discussed above. Polytechnic flares are of two types—those used in vertical drops, similar to a shotgun shell or flare-pistol cartridge, and the end-burning type, similar to warning flares. The flares contain silver iodide with or without an auxiliary oxydizer, such as potassium nitrate, together with aluminum, magnesium, and synthetic resin binder. Dropping flares are

⁶³ National Academy of Sciences, National Research Council, Committee on Atmospheric Sciences, "Weather and Climate Modification: Problems and Progress," Washington, D.C., 1973, pp. 115-16.

⁶⁴ *Ibid.*, p. 117.

⁶⁵ *Ibid.*, pp. 118, 120.

⁶⁶ *Ibid.*, pp. 119-120.

intended to be dropped into updrafts and to seed the cloud over a vertical depth as great as a kilometer, while burner seeding is intended to be more controlled and gradual. Hoppers dispense materials in solid form, such as the particles of dry ice crushed and dropped into clouds and cold fogs. For warm fog and cloud modification hoppers are used to dispense dry salt or urea. Sometimes these materials are pumped in a solution to nozzles in the wings, where the wingtip vortices help mix the agent into the air.⁶⁷

On the ground there are a number of seeding modes which are frequently used, and types of nucleants used with ground-based generators are commonly of two types—a complex of silver iodide and sodium iodide or of silver iodide and ammonium iodide. Outputs from the generator are usually from 6 to 20 grams per hour, although generators with much greater outputs are used sometimes. One seeding mode involves dispensing continuously into the airstream from a ground generator at a fixed point, the approach used most commonly in mountainous terrain. If the generator is located in flat country at temperatures above freezing, the nucleation level is reached through entrainment of the material into the convection.⁶⁸

The nucleating effectiveness of silver iodide smoke is dependent upon the cloud temperature, where the colder the temperature the greater is the number of ice crystals formed per gram of silver iodide. Tests of nucleating effectiveness are made in the Colorado State University cloud simulation facility, where the nucleant is burned in a vertical wind tunnel and a sample of the aerosol is collected in a syringe and nucleant density calculated from the pyrotechnic burn rate and the tunnel flow rate. The syringe sample is diluted with clean, dry air and injected into a precooled isothermal cold chamber containing cloud droplets atomized from distilled water. Ice crystals which grow and settle out are collected on microscopic slides, so that nucleating effectiveness can be calculated as the ratio of concentrated crystals detected to the mass of nucleating material in the air sample.⁶⁹

As part of the preparations for the 1976 seeding operations in the Florida area cumulus experiment (FACE) of the National Oceanic and Atmospheric Administration (NOAA), Sax et al., carefully evaluated the silver iodide effectiveness of different flares used in FACE. The results of these effectiveness studies, conducted with the Colorado State University facility, are shown in figure 14. It was discovered that a newly acquired airborne flare, denoted as NEI TB-1 in the figure, was considerably more effective than both the Navy flares used earlier and another commercially available flare (Olin WM-105). The superiority of the NEI TB-1 material at warmer temperatures is particularly noteworthy.⁷⁰ In another paper, Sax, Thomas, and Bonebrake observe that crystalline ice concentrations in clouds seeded in FACE during 1976 with the NEI flares greatly exceeded those found in clouds seeded during 1975 with Navy flares.

⁶⁷ Ruskin, R. E. and W. D. Scott, "Weather Modification Instruments and Their Use." In Wilmot N. Hess (ed.), "Weather and Climate Modification," New York, Wiley, 1974, pp. 193-194.

⁶⁸ Elliott, Robert D., "Experience of the Private Sector." In Wilmot N. Hess (ed.), "Weather and Climate Modification," New York, Wiley, 1974, p. 57.

⁶⁹ Sax, Robert L., Dennis M. Garvey, Farn P. Parungo, and Tom W. Slusher, "Characteristics of the AgI Nucleant Used in NOAA's Florida Area Cumulus Experiment." In preprints of the "Sixth Conference on Planned and Inadvertent Weather Modification," Champaign, Ill., Oct. 10-13, 1977. American Meteorological Society, Boston, 1977, p. 198.

⁷⁰ Ibid., pp. 198-201.

They conclude that, if differences in sampling time intervals and effects of instrumentation housing can be ignored, there is indicated a much greater nucleation effectiveness for the NEI flares which were used predominantly after July 1975.⁷¹ The implications of this result are very far reaching, since the borderline and/or slightly negative results of many previous experiments and operational projects can possibly be laid to the ineffectiveness of the silver iodide flares previously used.

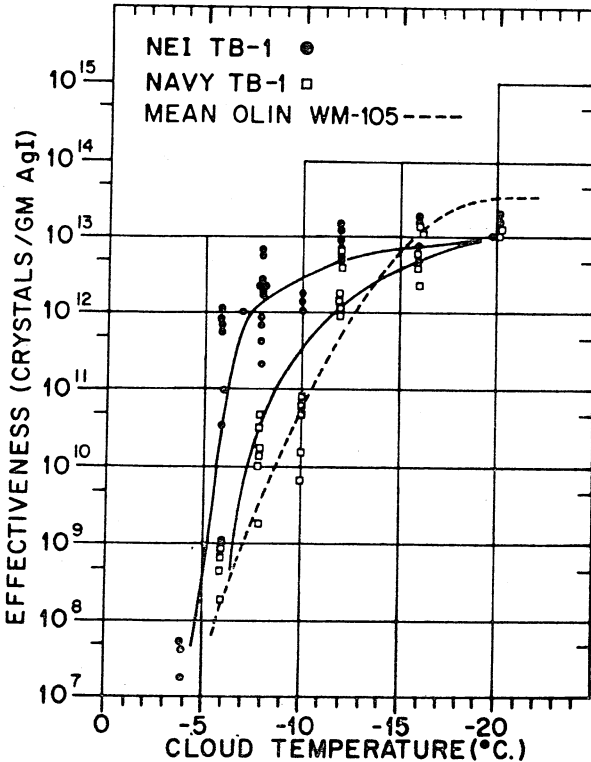


FIGURE 14.—Effectiveness of various silver iodide flares in providing artificial nuclei as a function of cloud temperature. The principal comparison is between the NEI TB-1 and the Navy TB-1 flares (see text) ; the curve of mean data for the Olin WM-105 flares is included for comparison. The curves show that the NEI flares, used in FACE in late 1975 and 1976 were significantly more effective in producing nuclei at warmer temperatures just below freezing. (From Sax, Garvey, Parungo, and Slusher, 1977.)

EVALUATION OF WEATHER MODIFICATION PROJECTS

There has been much emphasis on evaluation methodology on the part of weather modification meteorologists and statisticians, particularly with regard to precipitation modification. Progress in this

⁷¹ Sax, Robert I., Jack Thomas, Marilyn Bonebrake, "Differences in Evolution of Ice Within Seeded and Nonseeded Florida Cumuli as a Function of Nucleating Agent." In preprints of the "Sixth Conference on Planned and Inadvertent Weather Modification," Champaign, Ill., Oct. 10-13, 1977. Boston, American Meteorological Society, 1977," pp. 203-205.

area has been slow, owing to the complexity of verification problems and to inadequate understanding of cloud physics and dynamics.

Having reviewed previous considerations of evaluation attempts, Changnon discovered a wide variety of results and interpretations, noting that "a certain degree of this confusion has occurred because the methods being used were addressed to different purposes and audiences, and because there has been no widely accepted method of verification among investigators."⁷² He continues:

For instance, if one considers identification of changes in the precipitation processes most important to verification of modification efforts, then he will often undertake evaluation using a physical-dynamic meteorological approach. If he considers statistical proof of surface precipitation changes the best method, he may concentrate verification solely on a statistical approach or make inadequate use of the physical modeling concepts. On the other hand, if the evaluation is to satisfy the public, the consumer, or the governmental decision-maker, it must be economic-oriented also. Hence, a review of the subject of previous evaluation methodology must be constantly viewed with these different goals and concepts in mind.⁷³

Evaluation methodology for weather modification must deal with three fundamental problems which Changnon has identified:⁷⁴

1. There are many degrees of interaction among atmospheric forces that result in enormous variability in natural precipitation, greatly restricting attempts for controlled experiments that are attainable in other physical and engineering sciences.

2. There is an absolute need to evaluate weather modification with statistical procedures; this requirement will exist until all underlying physical principles of weather modification can be explained.

3. The data used in the evaluation must be sufficiently adequate in space and time over an experimental region to overcome and describe the natural variability factors, so that a significant statistical signal may be obtained within the noise of the variability.

It is further recognized that analysis of weather modification experiments is closely akin to the weather prediction problem, since evaluation of weather modification efforts is dependent on a comparison of a given weather parameter with an estimate of what would have happened to the parameter naturally. Thus, the better the prediction of natural events, the better can a weather modification project be designed and evaluated, at the same time reducing the verification time required by a purely statistical approach.⁷⁵

Initially, weather modification evaluation techniques used only the observational or "look and see" approach, improved upon subsequently by the "percent of normal" approach, in which precipitation during seeding was compared with normals of the pre-experimental period. Later, using fixed target and control area data comparisons, regression techniques were attempted, but the high variability of precipitation in time and space made such approaches inapplicable. In the mid-1960's there was a shift in sophisticated experiments toward use of randomization. In a randomized experiment, seeding events are selected according to some objective criteria, and the seeding agent is applied or withheld in sequential events or adjacent areas

⁷² Changnon, Stanley A., Jr., "A Review of Methods to Evaluate Precipitation Modification in North America," Proceedings of the WMO/IAMAP Scientific Conference on Weather Modification, Tashkent, U.S.S.R., Oct. 1-7, 1973. World Meteorological Organization. WMO—No. 399, Geneva, 1974, p. 397.

⁷³ Ibid., p. 398.

⁷⁴ Ibid.

⁷⁵ Ibid.

in accordance with a random selection scheme. An inherent problem with randomization is the length of experimental time required; consequently, the approach is not often satisfying to those who wish to obtain maximum precipitation from all possible rain events or those who want to achieve results in what appears to be the most economical manner. As a result, commercial projects seldom make use of randomization for evaluation, and such techniques are generally reserved for research experiments.⁷⁶

In very recent years the randomization approach, which to many appeared to be too "statistical" and not sufficiently meteorological in character, has been improved on through a better understanding of atmospheric processes, so that a physical-statistical approach has been adopted.⁷⁷

Changnon reviewed approximately 100 precipitation modification projects in North America and found essentially 6 basic methods that have been employed in project evaluations. He identified these as (1) direct observation (usually for single element seeding trials), (2) one-area continuous with no randomization (involving historical and/or spatial evaluation), (3) one-area randomization, (4) target-control area comparisons, (5) cross-over with randomization, and (6) miscellaneous.⁷⁸ These methods, along with the kinds of data which have been used with each, are listed in table 9.

TABLE 9.—REVIEW OF EVALUATION METHODS FOR PRECIPITATION MODIFICATION AND TYPES OF DATA EMPLOYED

[From Changnon, "A Review of Methods to Evaluate Precipitation Modification in North America," 1974]

Methods		Surface precipitation data	Meteorological elements data	Geophysical-economic data
Direct observation.....		Change in type; duration of precipitation; areal distribution (vs. model).	Cloud parameters; echo parameters; seed and plume.	
One-area continuous (nonrandom).	Historical.....	Area-rain regressions; weekend-weekday rainfall differences; frequency of rain days.	Frequency of severe weather; frequency of smoke days.	Added runoff; crop yields; ecological.
	Spatial.....	Area-rain regressions; pattern recognition; trend surfaces; rain rates; raindrop sizes; frequency of rain days; rain cell differences; precipitation type change; areal extent of rain.	Synoptic weather conditions; cloud parameters; echo parameters; AgI plumes; nuclei sources; airflow-plume behaviors; tracers in rain; atmospheric electrical properties.	Runoff increases; crop yields; ecological.
Target control.....		Area rainfall (day, month, season) regressions; area snowfall (day, month, season).	Echo parameters.....	Runoff regressions.
One-area randomized (hours pulsed).	Basically statistical.	Area precipitation; plume area precipitation; change in precipitation type. Period precipitation; echo area; rain rates; echo reflectivity; rain initiation.	Synoptic weather conditions; cloud parameters; seed material in plumes. Echo parameters; AgI in rain; cloud numerical models; storm behavior; cloud base rain rate.	Water yield; runoff; ecosystem (plant and animals) and erosion; avalanche—disbenefits.
	Physical plus statistical.	Area rainfall; zonal rainfall.	Synoptic types and upper air conditions.	
Crossover randomized.			Upper air: 1. Temperature. 2. Winds. 3. Moisture stability indices.	
Miscellaneous (post hoc stratifications).			Synoptic weather types.	

⁷⁶ Ibid., p. 399.

⁷⁷ Ibid., p. 400.

⁷⁸ Ibid., p. 407.

The direct observation technique was the first major approach to evaluation and is still used occasionally. In addition to direct observation of the change and type of precipitation at the surface, the time of precipitation initiation, and areal distribution following treatment of a cloud or cloud group, other meteorological elements have been observed; these include radar echo characteristics, plume of the seeding material, and cloud parameters (microphysical properties and dynamical and dimensional properties such as updrafts, cloud size, and rate of growth.).⁷⁹

The one-area continuous (nonrandomized) techniques have been employed to evaluate many of the commercially funded projects in North America, recent efforts to investigate inadvertent precipitation modification by large urban-industrial areas, and the statewide South Dakota seeding program. This category includes the largest number of projects, and control data for these nonrandomized projects have included both historical data and data from surrounding areas. The uncertainty of the control data as a predictor of target data is the basic problem in using this approach.⁸⁰

Most federally sponsored weather modification projects have used the one-area randomization method, which involves the use of a variety of precipitation elements, including duration, number of storms, and storm days and months. Projects evaluated with this method fall into two categories, including, as shown in table 9, those using the basic statistical approach and the more recent physical plus statistical techniques. The latter group of projects have been based on a greater knowledge of cloud and storm elements, using this information in defining seedable events and combining it with statistical tests to detect effects. Surface data, including rainfall rates and area mean rainfall differences, are used to evaluate such one-area randomized projects.⁸¹

The target-control method involves a single area that is seeded on a randomized basis and one or more nearby control areas that are never seeded and, presumably, are not affected by the seeding.⁸² The method had been used in about 10 North American projects through 1974. Evaluation data have been mostly area rainfall or snowfall regressions, runoff differences, and radar echo parameter changes.⁸³

The crossover (with randomization) method has been considered by many to be the most sophisticated of the statistical evaluation methods. The crossover design includes two areas, only one of which is seeded at a time, with the area for seeding selected randomly for each time period. As with the target-control method, a problem arises in this method in that there is the possibility of contamination of the control areas from the seeded area.⁸⁴ In the single project to which the method had been applied up to 1974, the evaluation procedure involved classification of potential treatment events according to meteorological conditions, followed by area and subarea rainfall comparisons.⁸⁵ The

⁷⁹ Ibid.

⁸⁰ Ibid., pp. 408-409.

⁸¹ Ibid., p. 409.

⁸² Brier, Glenn W. "Design and Evaluation of Weather Modification Experiments." In Wilmot N. Hess (editor), "Weather and Climate Modification," New York: Wiley, 1974, p. 209.

⁸³ Changnon. "A Review of Methods To Evaluate Precipitation Modification in North America," 1974, p. 409.

⁸⁴ Brier. "Design and Evaluation of Weather Modification Experiments," 1974, p. 210.

⁸⁵ Changnon. "A Review of Methods To Evaluate Precipitation Modification in North America," 1974, p. 409.

miscellaneous methods in table 9 refer basically to evaluation efforts that have occurred after but generally within the context of the five methods mentioned above, and have been largely post-hoc stratifications of results classified according to various meteorological subdivisions, followed by re-analysis of the surface rainfall data based on these stratifications.⁸⁶

TABLE 10.—REVIEW OF EVALUATION METHODS FOR HAIL MODIFICATION AND TYPES OF DATA EMPLOYED
[From Changnon "A Review of Methods to Evaluate Precipitation Modification in North America," 1974]

Methods	Surface hail data	Meteorological elements	Geophysical-economic
Direct observation.....	Cessation of hail; hail pattern; hail sizes change; hailstone character.	Echo parameters; cloud parameters; AgI in hail.	
One-area continuous (non-random).	Historical..... Number of hail days. Spatial..... Number of hail-producing clouds/unit time; hailstreak frequencies; number of hail days; rainfall characteristics; impact energy; location of hail vs. total precipitation area.	Radar echo characteristics.	Crop-hail loss (insurance); insurance rates. Crop-hail loss (insurance)
Target-control.....	Energy; hail day frequency.	Radar echo characteristics.	Hail loss (insurance).
One-area randomization.	Impact energy; hail day frequency; hailfall characteristics.	Radar echo characteristics; AgI in hail-rain.	Ecosystem (AgI); crop-loss data.
Cross-over randomized.	Energy; area of hail; volume of hail.	AgI in hail.	

About 20 projects concerned with hail modification were also analyzed by Changnon with regard to the evaluation techniques used. The five methods used, shown in table 10, include the first five methods listed in table 9 and discussed above for precipitation modification evaluation. A comparison of tables 9 and 10 reveals that the evaluation of rain and snow modification projects uses much less variety of kinds of data, especially the meteorological elements. The evaluation of hail projects is largely statistical, owing to the lack of sophistication in the physical modelling of hailstorms. There has been greater use of economic data in hail evaluation, however, than in evaluation of rainfall projects, due to some extent to the lack of surface hail data in weather records and the consequent need to make use of crop insurance data.⁸⁷

In hail evaluation, the direct observation method has been used to look at physical effects from seeding individual storms and storm systems, involving analysis of time changes in surface hail parameters, radar echo characteristics, and cloud properties. The one-area continuous (non-random) method has been the principal one used in commercial hail projects and in studies of inadvertent urban-industrial effects on hail, using historical and/or spatial data in the evaluation. One major data form in these evaluations is the crop-hail loss from insurance data. The target-control method has made use of hailfall energy, hail-day frequencies, and crop-hail loss as evaluation data.⁸⁸

⁸⁶ Ibid.

⁸⁷ Ibid., pp. 412-413.

⁸⁸ Ibid., p. 413.

The one-area randomization method is the method used in the National Hail Research Experiment.⁸⁹ Various degrees of randomization have been used, ranging from 50–50 to 80–20; however, the evaluation data have been similar to those used in other methods. Silver concentrations in samples of rain and hail and elsewhere in the ecosystem have been used as evaluation criteria. The crossover randomized method of evaluation has also been applied to hail projects, using such data as areal comparisons of impact energy, area extent of hail, and total hail volume, noting also the concentrations of seeding material in the hailstones.⁹⁰

A necessary part of any evaluation scheme involves the measurement or estimation of the amounts of precipitation fallen over a given area following seeded or control storm events. Such measurement is part of a more general requirement as well in collecting data for validation of weather predictions, development of prediction models, compilation of climatic records, and forecasting of streamflow and water resources. Although the customary approach to precipitation measurement has been to use an array of rain gages, weather radars have proven to be useful tools for studying generally the spatial structure of precipitation. Depending on the quality of the onsite radar system calibration, there have been varying degrees of success, however, in use of this tool. Often radar and rain gage data are combined in order to obtain the best estimate of precipitation over a given area. In this arrangement, the radar is used to specify the spatial distribution and the gauges are used to determine the magnitude of the precipitation.⁹¹

Exclusive use of rain gauges in a target area in evaluation of convective precipitation modification projects requires a high gauge density to insure adequate spatial resolution. For a large target area, such an array would be prohibitively expensive, however, so that weather radars are often used in such experiments. The radar echos, which provide estimates of precipitation, are calibrated against a relatively smaller number of rain gages, located judiciously in the target area to permit this calibration.

It has been shown that adjusted radar estimates are sometimes superior to either the radar or the gages alone. Furthermore, the best areal estimates are obtained using a calibration factor which varies spatially over the precipitation field rather than a single average adjustment. Erroneous adjustment factors may be obtained, however, if precipitation in the vicinity of the calibration gage is so highly variable that the gage value does not represent the precipitation being sampled by the radar. The technique for calculating the adjustment factor typically involves dividing the gage measurement by the summed rainfall estimates inferred from the radar, to obtain the ratio, G/R , used subsequently to adjust radar estimates over a greater area.⁹²

⁸⁹ The National Hail Research Experiment is discussed as part of the weather modification program of the National Science Foundation, ch. 5, p. 274ff.

⁹⁰ Changnon, "A Review of Methods To Evaluate Precipitation Modification in North America," 1974, p. 413.

⁹¹ Crane, Robert K., "Radar Calibration and Radar-rain Gauge Comparisons." In preprints of the "Sixth Conference on Planned and Inadvertent Weather Modification," Champaign, Ill., Oct. 10–13, 1977. Boston, American Meteorological Society, 1977, p. 369.

⁹² Kiazura, Gerald E., "Changes in Gage/radar Ratios in High Rain Gradients by Varying the Location and Size of Radar Comparison Area." In preprints of the "Sixth Conference on Planned and Inadvertent Weather Modification," Champaign, Ill., Oct. 10–13, 1977. Boston, American Meteorological Society, 1977, p. 376.

In the evaluation of hail suppression experiments, or measurements of hailfall in general, there must be some means of determining the extent and the magnitude of the hail. One technique is to use a network of surface instruments called hailpads. Since single storms can lay down hail swaths up to 100 kilometers long and tens of kilometers wide, made up of smaller patches called "hailstreaks," the spacings of hailpads must be reduced to a few hundred meters to collect quantitative data over small areas. Even over small distances of the order of 1 kilometer, it has been discovered that total numbers of hailstones, hail mass, and hail kinetic energy can vary by over a factor of 10.⁹³ Another means of estimating hailfall is through use of crop-damage studies. Such results are obtained through crop-loss insurance data, aerial photography of damaged fields, and combinations of these data with hailpad measurements.⁹⁴

EXTENDED AREA EFFECTS OF WEATHER MODIFICATION

The term "extended area effects" refers to those unplanned changes to weather phenomena which occur outside a target area as a result of activities intended to modify the weather within the specified target area. Such effects have also been called by a variety of other names such as "downwind effects," "large-scale effects," "extra-area effects," "off-target effects," and "total-area effects." When the time dimension is considered, those changes which occur, or are thought to have occurred, either within the spatial bounds of the target area or in the extended area after the intended effects of the seeding should have taken place are referred to as "extended time effects." These inadvertent consequences are usually attributed either to the transport of seeding material beyond the area intended to be seeded or the lingering of such material beyond the time during which it was to be effective.

In a number of experiments there have been indications that an extended area effect occurred. The present state of understanding does not permit an explanation of the nature of these effects nor have the experimental designs provided sufficient information to describe their extent adequately. The subject is in need of additional study, with experiments designed to provide more specific data over pertinent areal and time scales. In recent years two conferences on extended area effects of cloud seeding have been convened. The first conference, attended by 18 atmospheric scientists, was held in Santa Barbara, Calif., in 1971 and was organized by Prof. L. O. Grant of Colorado State University and by Robert D. Elliott and Keith J. Brown of North American Weather Consultants. Attendees at the 1971 seminar discussed existing evidence of extended area effects, considered the possible means of examining detailed mechanisms responsible for the effects, and debated the implications for atmospheric water resources management.

A second workshop was held, under the sponsorship of the National

⁹³ Morgan, Griffith M. and Neil G. Towery. "Surface Hail Studies for Weather Modification." In preprints of the "Sixth Conference on Planned and Inadvertent Weather Modification," Champaign, Ill., Oct. 10-13, 1977, p. 384.

⁹⁴ *Ibid.*

Science Foundation, at Colorado State University, Fort Collins, Colo., Aug. 8-12, 1977.⁹⁵ The Fort Collins meeting was attended by 44 participants, composed of social scientists, observationists, physical scientists, modellers, statisticians, and evaluators. The group was exposed to a mass of data from various weather modification projects from all over the world and proposed to accomplish the following objectives through presentations, workshop sessions, and general discussions:

Renew the deliberations of the Santa Barbara seminar.

Expand the scope of participation so as to integrate and interpret subsequent research.

Better define the importance of extended spatial, temporal, and societal effects of weather modification.

Prepare guidelines and priorities for future research direction.⁹⁶

Extended area effects have special importance to the nontechnical aspects of weather modification. From deliberations at the 1977 extended area effects workshop it was concluded that:

The total-area of effect concept adds a new dimension to an already complex analysis of the potential benefits and disbenefits of weather modification. A specified target area may have a commonality of interests such as a homogeneous crop in a farm area or a mountain watershed largely controlled by reservoirs built for irrigation and/or hydroelectric power generation. Socioeconomic analysis of this situation is much more direct than the consideration of the total-area of effect which may well extend into areas completely dissimilar in their need or desire for additional water. The spatial expansion of the area of effect may increase or decrease the economic and societal justification for a weather modification program. The political and legal consideration may also be complicated by this expansion in scope since effects will frequently extend across state or national borders.⁹⁷

The strongest evidence of extended area effects is provided by data from projects which involved the seeding of wintertime storm systems. Statistical analyses of precipitation measurements from these projects suggest an increase in precipitation during seeded events of 10 to 50 percent over an area of several thousand square kilometers. Some of the evidence for these effects, based mostly on post hoc analyses of project data, appears fairly strong, though it remains somewhat suggestive and speculative in general.⁹⁸

Based upon two general kinds of evidence: (1) observational evidence of a chemical or physical nature and (2) the results of large scale/long-term analyses; a workshop group examining the extended area effects from winter orographic cloud-seeding projects assembled the information in table 11. It should be noted that the quality of the evidence, indicated in the last column of the table, varies from "well documented" and "good evidence" to "unknown" and "no documentation available;" however, the general kinds of extended area and extended time effects from a number of winter projects are illustrated.⁹⁹

⁹⁵ Brown, Keith J., Robert D. Elliott, and Max Edelstein, "Transactions of Workshop on Extended Space and Time Effect of Weather Modification," Aug. 8-12, 1977, Fort Collins, Colo. North American Weather Consultants, Goleta, Calif., February 1978, 279 pp.

⁹⁶ *Ibid.*, pp. 7-9.

⁹⁷ *Ibid.*, p. 13.

⁹⁸ *Ibid.*, p. 10.

⁹⁹ Warburton, Joseph A., "Extended Area Effects From Winter-orographic Cloud Seeding Projects," report of workshop panel. In Keith J. Brown, et al., "Transactions of Workshop on Extended Space and Time Effects of Weather Modification," Aug. 8-12, 1977, Fort Collins, Colo. North American Weather Consultants, Goleta, Calif., February 1978, pp. 137-164.

TABLE 11.—EVIDENCE OF EXTENDED AREA EFFECTS FROM WINTER OROGRAPHIC SEEDING PROJECTS, BASED UPON EVIDENCE FROM (A) OBSERVATIONS AND (B) LARGE-SCALE/LONG-TERM ANALYSES

[From Warburton, 1978]

A. OBSERVATIONAL—PHYSICAL, CHEMICAL					
Observation	Type of effect	Magnitude of effect	Area of effect	Mechanism	Quality of evidence
Ice crystal anvil production from dry ice seeding of cumulus clouds, Blue Mountains, Australia.	Spatial and time.	Produced rain 6–12 mm over 18-hour period.	1500 km ²	Cirrus seeding and transport of crystals from seeding with Co.	Documentation needed (is available).
Persistence of ice nuclei at Climax—probably AgI for days after seeding.	Time.....	100×natural nuclei concentration.	Unknown.....	Unknown.....	Well documented (is available).
Transport of AgI from Climax generators to 30 km downwind.	Spatial.....	30 N/liter (–20° C).	~40 km ²	Transport of nuclei.	Few aircraft observations.
Silver in snow, Sierra Nevada and Rockies—up to 100 km from generators.	.....do.....	4 to 100× background.	Continuum from generators.	Physical transport of AgI on hydrometers containing AgI.	5 yr of observations.
Pressure reductions in seeded band periods, Santa Barbara.	Time.....	Max. –2 mb.....	Continuum from seeding sites (~1000 km ²).	Dynamic heating.	Fair to moderate documentation.
Cirrus shield produced by airborne seeding, Warragamba, Australia.	.....do.....	Up to 25 percent of seeded days.	2000 km ² (1 aircraft).	Ice crystal seeding of lower clouds.	Documentation needed (is available).
B. RESULTS OF LARGE-SCALE/LONG-TERM ANALYSES					
Projection description	Type of effect	Magnitude of effect	Area of effect	Quality of evidence	
Victoria, Australia, drought relief—non-randomized.	Spatial.....	30 percent > 40-yr, average, 3 successive yr.	35,000 km ² ; continuum from seeding sites.	No documentation available.	
Warragamba and other large-scale experiments—Australia decrease in S/NS ratio with years of experiment. ¹	Time; long-term.....	10 to 40 percent.....	Artifact of analysis.....	Reanalysis needed avoiding ratios and double ratios.	
Israel I—randomized north and central seeded.	Spatial.....	+25 percent.....	6,000 km ² ; continuum from seeding sites.	Reliable records for analysis.	
Santa Barbara band seeding—randomized.	.....do.....	+25 percent (+50 percent in bands).	3,000 km ² ; continuum from seeding sites.	Moderately well documented.	
Santa Barbara storm seeding of multiple bands.	.....do.....	Unknown.....	Unknown.....	Unknown.	
Santa Barbara duration of seeded/nonseeded bands.	Time.....	Seed/no seed ratios of 1.5 to 4 mean 50 percent-increase.	3,000 km ² ; continuum from seeding sites.	Good evidence.	
Climax and east to plains of Colorado using "homogeneous" data base determined by new synoptic technique.	Spatial.....	Unknown analysis continuing.	600 km ² ; 130 km east of Climax, 30 to 50 km south of Denver.	Speculative.	

¹ Tasmania experiment may confirm artifact.

Examination of data from summertime convective cloud-seeding projects reveals "more mixed" results by comparison with data from wintertime projects, when extended area effects are considered. This general conclusion accords with the mixed results from evaluations of convective cloud seeding within the target area. It was concluded by participants on a panel at the 1977 Fort Collins workshop that, for summertime convective cloud seeding, there are statistical evidences of both increases and decreases in the extended area, though there are a large number of nonstatistically significant indications. Table 12 was assembled by the panel to summarize the characteristics of these effects for each of the projects examined.¹

¹ Smith, T. B., "Report of Panel on Summer Weather Modification." In Keith J. Brown, et al., "Transactions of Workshop on Extended Space and Time Effects of Weather Modification." Aug. 8–12, 1977, Fort Collins, Colo. North American Weather Consultants, Goleta, Calif., February 1978, pp. 228–326.

TABLE 12.—EVIDENCE OF EXTENDED AREA EFFECTS FROM SUMMERTIME CONVECTIVE WEATHER MODIFICATION PROGRAMS
[From Smith, "Report of Panel on Summer Weather Modification," 1978]

Project	Size of area			Experiment unit	Sample size	Seeding			Overall effect		Mechanism guesses		
	Target (square miles)	Extended (miles)	Day			Mode	Rate	Material	Target	Extended	Target	Extended	
Grossversuch (1957-63)- Arizona (1957-64)	625	120	Day	145/147	-----	GB in Mts	20g 14 hr	AgI	+S A	+S A	Dynamic; warm moist air.	Propagation convection.	
	300	65	Day	106/106	-----	AC-6°C Patrol	2 to 4 hr 15 to 20 mi	AgI	-NS A	-NS A	Dynamic overseed	Dynamic stabilization.	
		180		37/37	-----	AC CB Patrol	2,000 g/hr 4,000 to 8,000 g/d						
Whitetop (1960-64)	11,300	60	Day	102/96	-----	3 AC CB	≤6 hr	AgI	-S A	-S A	Pumped all water out top; less moist air.	Do.	
		120			-----	Patrol	30 mi long						
		180			-----		2,700 g/hr						
		300			-----		16,200 g/d						
Colorado (1966-69)	1,000	200	Day	116/125	-----	GB 3 gen.	22 hr 15 g/hr 1,080 g/d		A -NS	A -NS	Pumped all water out top; warm moist air.	No effect.	

FACE (1970-76)	4,000	120	Day	39/36	-----	AC top -10°C	800 g/cloud 10,000 to 50,000 g/d	AgI	A FT +S TT +NS	B C	Dynamic mesoscale organization; sea breeze process.		

NHRE (1972-74)	625	150	Day	27/30	-----	AC CB Rockets	3,000 g/d 1,000/system	AgI	+NS B	0 C	Microphysical static seeding.	Do.	

Israel (1972-76)	1,000	50	Day	275 cross-over design.	-----	AC CB Patrol	500 g/hr	AgI	B +15%	C (NS) (S)	do		

South Dakota (1966-68)- North Dakota (1969-72)	700		Day	54/54	-----	AC CB GB	300 g/hr 15/40 g/hr	AgI	B -NS	B -NS	Dynamic and microphysical.		
	5,300		Day	277/91	-----	AC CB	300 g/hr	AgI	-NS -NS	+NS -Upwind			

1 2d-day effect suggested by Howell.

Key: GB—ground based; AC—aircraft; CB—cloud base; S—significant; NS—not significant; A, B, C—data quality.

It was the general consensus of the 1977 workshop participants that seeding can effect precipitation changes over relatively large areas which extend beyond the typical target area. Such changes can be positive or negative and may be of the same sign as the effect in the designated target area or of opposite sign. For example, among summertime projects considered the Israeli experiment provided substantial evidence for positive effects in the target and in the extended areas (see table 12). Project Whitetop and the Arizona experiment, on the other hand, showed strong evidence of precipitation decreases in the target areas, downwind, and in surrounding areas. The Florida area cumulus experiment (FACE) revealed significant rainfall increases in the target area, but seemed to show decreases in surrounding areas, and the 1969-1972 South Dakota project demonstrated negative seeding effects in the target area and positive effects in extended areas. Of all projects reviewed, however, and in view of all the differing results suggested, the combination of target- and extended-area effects which appears to have the least support is that combination most likely to occur to many lay people, i.e., increases in the target area with compensating decreases in some area "downwind"—the "robbing Peter to pay Paul" analogy.²

Statistical evidence of extended area and time effects seems to be reasonably common; however, the mechanics causing these effects are not understood. It appears that there may be a number of mechanisms which come into play, the dominating ones operating under various storm types and seeding techniques. In some projects there is evidence that seeding intensified the storm dynamically through release of latent heat of sublimation. In other cases silver iodide has been transported for distances of 100 kilometers downwind of the seeding area and has persisted for several days in the atmosphere after seeding. Also ice crystals produced from seeding may, in turn, seed lower clouds downwind.³

With particular regard to extended area or time effects in cumulus seeding experiments, Simpson and Dennis have identified the following list of possible causes:

1. Physical transport of the seeding agent.
2. Physical transport of ice crystals produced by a seeding agent.
3. Changes in radiation and thermal balance, as for example, from cloud shadows or wetting of the ground.
4. Evaporation of water produced.
5. Changes in the air-earth boundary, such as vegetation changes over land or changes in the structure of the ocean boundary layer following cloud modification.
6. Dynamic effects:
 - (a) Intensified subsidence surrounding the seeded clouds, compensating for invigorated updrafts.
 - (b) Advection or propagation of intensified cloud systems which subsequently interact with orography or natural circulations.
 - (c) Cold thunderstorm downdrafts, either killing local convection or setting off new convection cells elsewhere.

² Brown, et al. "Transactions of the Workshop on Extended Space and Time Effects of Weather Modification," 1978, p. 11.

³ Ibid., p. 12.

(d) Extended space-time consequences of enhancement or suppression of severe weather owing to cumulus modification.

(e) Alteration, via altered convection, of wind circulation patterns and/or their transports which could interact with other circulations, perhaps at great distances.⁴

Recommended research activities to further explore and develop understanding of extended area and extended time effects of weather modification are summarized in the final section of this chapter, along with other research recommendations.⁵

APPROACHES TO WEATHER MODIFICATION OTHER THAN SEEDING

Nearly all of the techniques discussed earlier for modifying the weather involve some kind of "cloud seeding." The exception is in the case of warm fog dispersal, where attempts to dissipate have also included mechanical mixing or application of heat. While most cloud-seeding techniques involve the use of artificial ice nuclei such as those provided by silver iodide particles, other "seeding" substances, such as dry ice, sodium chloride, urea, propane, and water spray, have been used in certain applications. Clouds have also been seeded with metalized plastic chaff in order to dissipate electrical charge build-up and reduce the incidence of lightning.

There may also be some promise in future years of beneficially changing the weather, over both large and small scales of time and space, using technologies that are not in the general category of cloud seeding. Indeed, some such schemes have been proposed and there has been research conducted on a number of these possibilities.

In the following chapter the effects of man's activities and some natural phenomena in changing the weather unintentionally will be discussed. While these inadvertent effects may be of general concern and should be studied in view of potential dangers, they should also be understood inasmuch as they may provide valuable clues on how the atmosphere can be more efficiently modified for beneficial purposes. For example, major heat sources judiciously located might be used to affect weather in ways useful to man.

Solution of problems which overlap considerations of both weather and energy could be investigated and solved in common by scientists and engineers working in both fields. Such research should be underway and some practical applications could be forthcoming during the 1980's. Dissipation of supercooled clouds and fog over large and medium-sized cities, which now appears to be technically feasible, may become desirable when solar energy collectors are more common. Reduction of radiative losses to space could be facilitated by allowing the clouds to reform at night. It is speculated that this diurnal cycle of operation would tend to weaken inversions that are often associated with fog and low stratus and so tend to alleviate problems of air pollution, though there might be some increase of photochemical effects in the daytime with additional sunlight.⁶

Excess heat and moisture from nuclear and other powerplants and from their cooling towers could be usefully employed for generating

⁴ Simpson and Dennis, "Cumulus Clouds and Their Modification," 1974, pp. 274-277.

⁵ See p. 143.

⁶ Dennis and Gagin, "Recommendations for Future Research in Weather Modification," 1977, p. 79.

clouds if the plants are optimally located with regard to water sources and meteorological conditions. The clouds so formed might be used for protection to crops during periods of intense heat or as a shield over a city at night to prevent re-radiation of heat back to space. The clouds might also be seeded subsequently somewhere downwind of the power-plant to enhance precipitation.

Recently, Simpson reviewed and summarized the state of research and development of a number of the nonseeding approaches to weather modification which have been proposed.⁷ She discusses effects of changes to radiation and to sea-air interface processes:

Some expensive, brute force successes have been obtained by burning fuels to clear fogs or even to create clouds. A more ingenious approach is to use solar heat to alter part of the air-surface boundary or a portion of the free atmosphere. Black and Tarmy (1963) proposed ten by ten kilometer asphalt ground coatings to create a "heat mountain" to enhance rain, or to reduce pollution by breaking through an inversion. Recently Gray, et al. (1975) have suggested tapping solar energy with carbon dust over 100-1,000 times larger areas for numerous weather modification objectives ranging from rain enhancement to snow melt, cirrus production, and storm modification. The physical hypotheses have undergone preliminary modelling with promising results, while the logistics appear marginally feasible. Drawbacks are the unknown and uncontrollable transport of the dust and its environmental unattractiveness.

A cleaner way of differentially heating the air appears to be a possible future byproduct of the space program. A Space Solar Power Laboratory is in the planning stages at NASA. Its main purpose is to provide electric power, which will be sent by the space laboratory to the earth's surface. The microwave power will be converted to DC by means of groups of rectifying antennas, which dissipate a fraction of the power into heat. Preliminary calculations * * * indicate that the atmospheric effect of the estimated heating would be comparable to that by a suburban area and thus could impact mesoscale processes. Future systems could dissipate much more heat and could conceivably be a clean way to modify weather processes. It is not too soon to begin numerical simulation of atmospheric modifications that later generation systems of this type might be able to achieve.

Radiation alteration appears to be a hopeful weather modification approach still lacking a developed technology. A cirrus cover has long been welcomed as natural frost protection when it restricts the nocturnal loss of long-wave radiation. More recently, the effect of cirrus in cutting off short-wave daytime radiation has been modelled and measured. * * * Artificial simulation of cirrus effects by minute plastic bubbles impregnated with substances to absorb selected wavelengths received preliminary attention . . . but, to my knowledge has not been pursued.

Alteration of the sea-air interface is also a potentially promising weather modification technique, particularly to suppress convection or to mitigate the destruction by tropical hurricanes. However, the technology in this area may be farther from actual field trials than that in radiation. If methods could be developed to restrict sea-air latent and sensible heat flux, the development from tropical storm to hurricane might be inhibited, while not losing rainfall or other benefits of the system. Presently the monomolecular films which cut down the evaporation from reservoirs do not stay intact in oceanic storm conditions, even if the logistics of their delivery over wide areas ahead of the storm were solved. Logistic obstacles have also impeded implementation of the promising idea of cooling the waters ahead of the hurricane by mixing up the ocean layer above the thermocline.⁸

One possible means of achieving the mixing of ocean layers to cool the sea surface, suggested above by Simpson, might be accomplished,

⁷ Simpson, Joanne, "What Weather Modification Needs," 1977, unpublished, pp. 13-15. (Most of the needs of weather modification identified in this unpublished paper, but not including her summary of nonseeding approaches, were published in another paper with the same title by Dr. Simpson: preprints of "Sixth Conference on Planned and Inadvertent Weather Modification," Champaign, Ill., Oct. 10-13, 1977. Boston, American Meteorological Society, 1977, pp. 304-307.

⁸ *Ibid.*

at least in part, as a beneficial byproduct of another power source under development—the ocean thermal energy conversion (OTEC) concept. The OTEC plants, located in tropical waters where hurricanes are spawned and grow, can provide surface cooling and so assist, at least in localized areas, in the abatement of tropical storms and their attendant damages. This is another area of overlap between energy and weather interests where cooperative research and development ought to be explored.

RESEARCH NEEDS FOR THE DEVELOPMENT OF WEATHER MODIFICATION

In previous sections of this chapter the rationale and the status of development of the various techniques used to modify several kinds of weather phenomena were summarized and discussed in some detail. Applications of these techniques in both operational and research projects were considered and some measures of the current effectiveness were presented. Among these discussions were a variety of statements, some explicit and some implied, on further research necessary to advance weather modification technology. This section addresses research needs more generally and in a more systematic manner. Included are specific requirements and recommendations identified by individual experts and organizations. Recommendations of a policy nature on weather modification research, such as the role of the Federal Government and the organizational structure for managing research, are discussed in chapter 6, which summarizes the recommendations of major policy studies. Current research programs of Federal agencies are discussed in some detail in chapter 5.

Research recommendations summarized in this section are primarily concerned with advancing the technology of advertent weather modification intended for beneficial purposes. Research needs in support of other aspects of planned weather modification and on inadvertent modification are included in other chapters on those subjects. In some cases, however, in the following sets of recommendations, research efforts in these other areas are included with those dealing with technology improvement in order to preserve the completeness of the particular set of recommendations.

GENERAL CONSIDERATIONS

Peter Hobbs identifies four main phases through which most developing technologies such as weather modification must pass—the establishment of scientific feasibility, engineering development, demonstration projects, and full-scale plant operation.⁹ He illustrates these phases in terms of relative expenditures and elapsed time for each in figure 15 and discusses the probable stage of development for weather modification. Noting that some would optimistically place development of the technology as far along as the dashed line YY, he himself would more cautiously place the progress of weather modification in the vicinity of XX, so that the major task ahead remains as the testing of the scientific feasibility to produce significant artificial modification to the weather.¹⁰

⁹ Hobbs, Peter V., "Weather Modification; a Brief Review of the Current Status and Suggestion for Future Research." Background paper prepared for the U.S. Department of Commerce Weather Modification Advisory Board, March 1977, p. 10.

¹⁰ *Ibid.*

This scientific feasibility can best be shown, according to Hobbs, through "mounting comprehensive research programs to investigate the structure and natural processes which dominate a few relatively simple cloud and precipitation systems and to establish the extent and reliability with which they can be artificially modified." He cites as a principal reason for the lack of significant progress in recent years his contention that "most of the effort has been directed at attempts to modify very complicated storm systems about which little is known and good hypotheses for artificial modification are lacking."¹¹

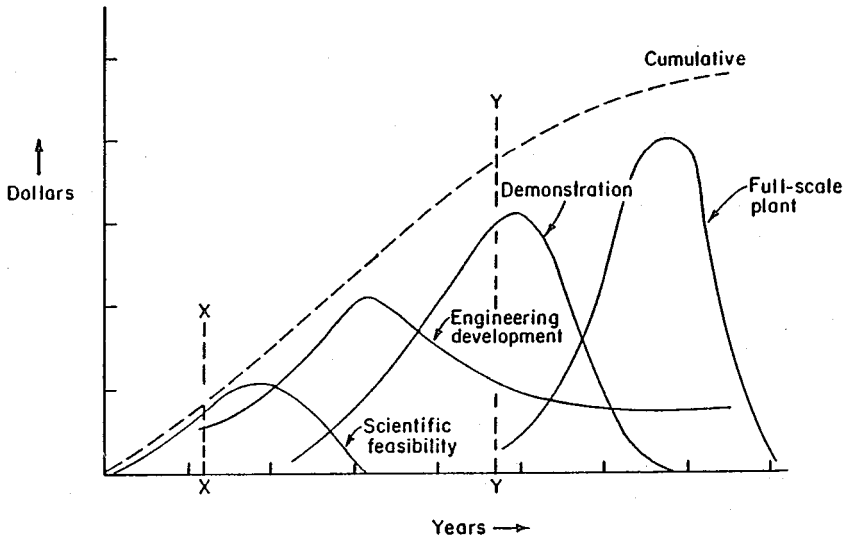


FIGURE 15.—Schematic of the relative costs and time associated with the four phases of development of a new technology. The vertical lines XX and YY indicate two widely differing views on the present stage of development of weather modification technology. (From Hobbs, 1977.)

We have seen that there is some reason to accept weather modification techniques as having some degree of operational capability in possibly two areas—cold fog dispersal and snowfall enhancement from orographic clouds—though there is room for continued research and technique development in these as well as other areas of weather modification. Although supercooled fogs account for only 5 percent of all fog occurrences, their prevalence at airports in northeastern and northwestern North America makes cold fog dispersal a valuable tool. Seeding of wintertime orographic clouds in experiments and operational projects in the western United States has probably resulted in snowfall increases of 10 to 30 percent under certain conditions.

Table 13 is a review and general outlook on weather modification, prepared by Changnon, showing the stage of development, possible economic value or years before operational usefulness, and status of research for 5 areas of weather modification, for the cold-temperature and warm-temperature cases where applicable. The table also shows Changnon's rough estimate of the complexity and difficulty in

¹¹ *Ibid.*, pp. 10-12.

relation to fog dispersal of the development of modification techniques for the other phenomena.¹²

Changnon emphasizes the fact that established techniques do not exist for significant modification of weather phenomena such as rainfall and severe weather over the more populous and major agricultural areas of the eastern United States. He says that:

If measurable economic gains are to be realized in the eastern two-thirds of the United States due to weather modification (largely rain "management", hail suppression, and abatement of severe winter storms), much more research and effort must be extended. This research will concern (1) the thorough study on a regional scale of the complex multicellular convective systems which are the major warm season rain and hail producers, and (2) the study of the cold season cyclonic systems.¹³

TABLE 13.—OUTLOOK FOR PLANNED WEATHER MODIFICATION IN UNITED STATES

[From Changnon, "Present and Future of Weather Modification; Regional Issues," 1975]

	Fog	Orographic precipitation	Convective rainfall	Severe convective storms	Cyclonic scale storms
Cold temperatures (<32° F).	Operational phase; low cost; research declining.	Operational phase (+10 to +30 percent); low cost; research declining.	Research phase; favorable on small clouds; questionable on large clouds and systems; substantial research.	Research phase; 5 to 10 yrs before operational; substantial and increasing research.	Exploratory phase; more than 10 yrs; research on tropical is modest; research on "other" storms is minor.
Warm temperatures (>32° F).	Research phase; 2 to 5 yrs: substantial and increasing research.	Possible phase; little research. ¹	Exploratory phase; modest research. ¹	-----	-----
Degree of complexity (in relation to fog).	1.0-----	10-----	100-----	1,000-----	10,000.

¹ Questionable economic value unless chain reaction is found.

Hobbs discusses in detail some of the kinds of weather modification research projects which he feels would be fruitful:

Some candidate projects for intensive investigation include the dispersal of cold and warm fogs, the enhancement of precipitation from isolated continental-type cumulus clouds, and the targeting of winter orographic snowfalls. Our knowledge of each of these subjects has reached the stage where the mounting of comprehensive projects is likely to yield definitive results. Physical studies have demonstrated that cold fogs can be dissipated by seeding with dry ice, and this technique is now in use operationally at a number of airports; however, a statistical study to quantify the reliability of this technique has not (to my knowledge) been carried out. It could provide the much needed "success story" for weather modification. The dispersal of warm fogs is a much more difficult problem which has not yielded to subtle approaches. The U.S. Air Force has concluded that the best approach to this problem is through direct heat input; this approach appears sufficiently promising that it should be subjected to proper physical and statistical evaluation. The possibility of targeting winter orographic snowfall to specific areas on the ground (e.g., reservoirs) has been investigated. . . . The technique shows sufficient promise that further studies involving both physical and statistical evaluation should be carried out. Attempts at modifying the precipitation from cumulus clouds dates back to the beginning of modern weather modification (the 1940's); however, very few of these projects have involved both physical and statistical evaluation (and many have used neither).

¹² Changnon, Stanley A., Jr., "Present and Future of Weather Modification; Regional Issues," 1975, pp. 172-174.

¹³ Ibid., p. 172.

In view of our growing understanding of the structure and life cycles of individual cumulus clouds, and the advances which have been made in the numerical simulation of these processes, the time is now ripe to mount a substantial investigation to determine whether precipitation from these clouds can be increased.

The primary components of the comprehensive research projects recommended above should be physical, statistical, and theoretical analysis. Physical evaluations should include comprehensive field studies using a wide range of airborne, ground, and remote probing techniques to evaluate the natural systems and the degrees to which they can be artificially modified. Physical testing and evaluation of a proposed weather modification technique is best commenced prior to the establishment of a statistical design, for not only can physical evaluations check the feasibility of a proposed technique, but they can indicate the conditions under which it is most likely to be effective and thereby aid in sharpening or the statistical design. A sound weather modification technique should also be based on, or supported by, the best theoretical models available for describing the weather system under investigation. If the theoretical and physical studies indicate that a particular weather modification technique is effective, a carefully designed randomized statistical experiment should follow. Theoretical and physical evaluations should continue through the statistical experiment. An independent repetition of the experiment in at least one other geographical area will generally be required. The confluence of results from theoretical, physical, and statistical analyses carried out in two areas would permit sound quantitative evaluation of the effectiveness of an artificial modification technique.¹⁴

RECOMMENDATIONS FROM THE 1973 NATIONAL ACADEMY OF SCIENCES STUDY

In the 1973 study published by the National Academy of Sciences¹⁵ three broad research goals for weather modification were recommended along with specific research programs and projects required to achieve those goals. The three goals are:

1. Identification by the year 1980 of the conditions under which precipitation can be increased, decreased, and redistributed in various climatological areas through the addition of artificial ice and condensation nuclei;
2. Development in the next decade of technology directed toward mitigating the effects of the following weather hazards: hurricanes, hailstorms, fogs, and lightning; and
3. Establishment of a coordinated national and international system for investigating the inadvertent effects of manmade pollutants, with a target date of 1980 for the determination of the extent, trend, and magnitude of the effect of various crucial pollutants on local weather conditions and on the climate of the world.¹⁶

Achievement of these national goals would require, according to the National Academy study, implementation of the following research efforts, some in support of all three goals and others as a means to achieving each of the three goals:

A. Recommended research in support of all three goals:

1. More adequate laboratory and experimental field programs are needed to study the microphysical processes associated with the development of clouds, precipitation, and thunderstorm electrification.

¹⁴ Hobbs, "Weather Modification;" a Brief Review of the Current Status and Suggestions for Future Research," 1977, pp. 12-13.

¹⁵ National Academy of Sciences, "Weather and Climate Modification; Problems and Progress," 1973.

¹⁶ *Ibid.*, p. 27.

2. There is a need to develop numerical models to describe the behavior of layer clouds, synoptic storms, orographic clouds, and severe local clouds.

3. There is a need for the standardization of instrumentation in seeding devices and the testing of new seeding agents.

4. There should be established a number of weather modification statistical research groups associated with the major field groups concerned with weather modification and the inadvertent effects of pollutants.

5. There should be created a repository for data on weather modification activities, and, at a reasonable price, such data should be made available for reanalyses of these activities.

B. Recommended research in support of goal 1 above:

1. There is a continuing need for a comprehensive series of randomized experiments to determine the effects of both artificial and natural ice and cloud nuclei on precipitation in the principal meteorological regimes in the United States.

2. Investigations into the feasibility of redistributing winter precipitation should be continued and expanded.

3. Experiments need to be designed so that the effects of seeding on precipitation outside the primary area of interest can be evaluated.

4. Studies of the effects of artificial seeding on cumulus clouds and the numerical modeling of the seeding process should be continued and expanded.

C. Recommended research in support of goal 2 above:

1. Investigations should be made to determine whether the seeding techniques presently used in the study of isolated cumulus clouds and in hurricane modification can be extended to, or new techniques developed for, the amelioration of severe thunderstorms, hailstorms, and even tornadoes.

2. An expanded program is needed to provide continuous birth-to-death observations of hurricanes from above, around, within, and beneath seeded and nonseeded hurricanes and for testing of existing and new techniques for reducing hurricane intensities.

3. Studies on the development of hurricane-modification techniques should include a randomization scheme in the design and conduct of experimental programs.

4. A major national effort in fundamental research on hailstorms and hailstorm modification should be pursued aggressively.

5. A comprehensive program dealing with research on warm fog and its dissipation should be undertaken.

6. A high priority should be given to the development of a variety of research techniques specifically designed for observing severe storms.

D. Recommended research in support of goal 3 above:

1. National and international programs should be developed for monitoring the gaseous and particulate content of the atmosphere, with particular emphasis on modification by man's activities.

2. Satellite programs should be developed to monitor continually, on a global basis, the cloud cover, albedo, and the heat balance of the atmosphere.

3. There should be enlarged programs to measure those parameters that describe the climate of cities and adjoining countryside and to determine the physical mechanisms responsible for these differences.

4. Continued strong support should be provided to the major effort now underway, known as the Global Atmospheric Research Program, to develop properly parameterized mathematical models of the global atmosphere-ocean system, to obtain the observational data to test their efficacy, and to provide the computers that permit simulation of the effects of human activities on a worldwide scale.¹⁷

Some of the recommended research activities discussed above were already underway at the time of the 1973 National Academy study, but continuation or expansion of these efforts were advised. Since that time others have been initiated, and beneficial results from continuation and expansion of earlier efforts have been achieved. The overall decrease in funding of the Federal research program in the past few years has resulted in curtailments of valuable research projects identified to meet the goals above, however, and the current level of research activities can hardly lead to achievement of the goals set by the Academy study. The recent history of Federal funding for weather modification is discussed and summarized in chapter 5, as part of the treatment on Federal activities.¹⁸

RECOMMENDATIONS OF THE ADVANCED PLANNING GROUP OF NOAA

Concerned that its research programs be more responsible to societal needs, the Weather Modification Project Office of the National Oceanic and Atmospheric Administration (NOAA) established a small advanced planning group in 1976. Consisting of one full-time and three part-time members, none of whom were permanent NOAA employees, the advanced planning group was charged with making recommendations and preliminary plans for research projects to be carried out over the following 10 to 15 years. The group set about its task by visiting various user groups to learn opinions about past Federal research and by reviewing available literature and consulting scientists on past and current weather modification field programs.¹⁹

The advanced planning group acknowledged that considerable progress had been made in weather modification in the past few years, but noted that the current research approach has the following shortcomings:

1. Research in the United States on stimulation of precipitation has been concentrated in the semiarid western States and in Florida rather than in the Corn Belt, where the potential economic payoff is much greater.

2. Research on stimulation of rainfall and on suppression of hail and lightning have been carried out in separate projects. A single project dedicated to the concept of precipitation management in large convective clouds would be more likely to solve the problem of changing hailfall and rainfall simultaneously to produce net economic benefits.

¹⁷ Ibid., pp. 27-30.

¹⁸ See p. 242.

¹⁹ Dennis. Arnett S. and A. Gagin, "Recommendations for Future Research" in Weather Modification, Weather Modification Program Office, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Boulder, Colo., November 1977, 112 pp.

3. Weather modification has usually been equated with cloud seeding. Other possible means of modifying the weather have been largely ignored.

4. Weather modification is usually considered in isolation, rather than as an integral part of a total response to weather-related problems. There are exceptions: dry ice seeding to improve visibility during cold-fog episodes at airports is normally viewed as a supplement to, rather than a replacement for, good instrument landing systems. However, cloud seeding to increase precipitation is sometimes viewed as an alternative to irrigation or water conservation measures, a situation we think is regrettable. Fortunately, research in inadvertent weather modification is tending to break down the artificial isolation of research related to weather modification from other aspects of atmospheric science.²⁰

Having examined the current weather modification research situation as perceived by user groups and research scientists, the NOAA Advanced Planning Group proceeded to formulate recommendations for future research, using certain general technical, economic and sociological guidelines. Proposed research was evaluated on the basis of answers to the following questions:

1. Will the project advance scientific understanding of atmospheric processes and thereby contribute to an improved capability to modify weather on a predictable basis?

2. Will the operational capability toward which the project is directed provide net economic benefit?

3. Are the proposed research and the possible subsequent applications socially acceptable?²¹

The group completed its study during 1977 and provided its recommended research program to NOAA's Weather Modification Project Office. The 5 specific recommendations are summarized below:

1. Work should be continued to determine the potential for increasing rainfall from convective clouds in warm, humid air masses by seeding for dynamic effects. Design of a new, comprehensive project to be conducted in the eastern half of the United States should begin immediately. This project should gather information on the effects of seeding upon rainfall, hail, lightning, and thunderstorm winds both within and outside a fixed target area. Additional field studies in Florida to establish the physical mechanisms responsible for the apparent increases in total target rainfall during FACE²² in 1975-76 should be performed during at least two seasons in parallel with the design of the new project. The results of the additional studies would be valuable input for the design of the new comprehensive experiment.

2. Because of the promising beginnings of the Sierra Cooperative Project on orographic precipitation and the HIPLEX²³ work on cumulus clouds in the semiarid western States, and because the projects are likely to produce important results of wide applica-

²⁰ Ibid., p. 8.

²¹ Ibid., pp. 8-9.

²² The Florida Area Cumulus Experiment (FACE), an experimental project sponsored by NOAA's discussed under activities of the U.S. Department of Commerce in ch. 5, p. 292.

²³ The Sierra Cooperative Project and the High Plains Cooperative Program (HIPLEX) are projects sponsored under the Division of Atmospheric Water Resources Management of the Bureau of Reclamation in the U.S. Department of the Interior. These projects are discussed in ch. 5, pp. 258 and 263, respectively.

tion, we see no reason for new initiatives in these areas until those projects are completed.

3. In view of the need for more detailed knowledge of hurricane behavior, we recommend that research on hurricane modification be continued with the understanding that the research is a long-term effort with potential payoff 10 to 20 years away. We recommend further that modeling and other theoretical work be intensified to provide a better basis for interpretation of data from seeding trials.

4. Concepts for hail suppression and lightning suppression should be subjected to fundamental reappraisal before the resumption of any field experiments.

5. Long-range planning should be continued toward "futuristic" projects in which problems in deliberate, large-scale weather modification, inadvertent weather modification, forecasting, and agricultural climatology would be treated together rather than separately.²⁴

SUMMARY OF FEDERAL RESEARCH NEEDS EXPRESSED BY STATE OFFICIALS

At the request of NOAA's Advanced Planning Group, whose study was discussed in the previous section, the North American Interstate Weather Modification Council (NAIWMC)²⁵ compiled information on recommended Federal weather modification research, based on the needs of users within NAIWMC member States. Opinions of State officials on needed research were obtained from 16 States through meetings sponsored by California, North Dakota, Pennsylvania, South Dakota, Texas, and Utah and through questionnaires sent out by the NAIWMC during 1976 and 1977.

Table 14 summarizes results of the NAIWMC investigation, showing perceived needs for research for weather modification users, as interpreted by the State officials.²⁶ Keyes notes that the major research area recommended by most State and local governments is in the evaluation of ongoing, long-term operational projects within those States. Other important research needs expressed were for further development of seeding technology and for economic, environmental, and societal studies necessary for eventual public acceptance of weather modification.²⁷

²⁴ *Ibid.*, pp. 11-12.

²⁵ The purposes, organization, and activities of the North American Interstate Weather Modification Council are discussed in some detail in ch. 7, p. 333.

²⁶ Keyes, Conrad G., Jr., "Federal Research Needs and New Law Requirements in Weather Modification: the NAIWMC Viewpoint," testimony before the U.S. Department of Commerce Weather Modification Advisory Board, Champaign, Ill., Oct. 14, 1977.

²⁷ *Ibid.*

TABLE 14.—SUMMARY OF FEDERAL WEATHER MODIFICATION RESEARCH NEEDS, DETERMINED FROM OPINIONS OF STATE OFFICIALS DURING STATE MEETINGS AND THROUGH QUESTIONNAIRES FROM THE NORTH AMERICAN INTERSTATE WEATHER MODIFICATION COUNCIL

[From Keyes, 1977; table format from Dennis and Gagin, 1977]

State	Major categories of research ¹					
	1	2	3	4	5	6
Arizona.....	a, b, c.....	a, b, e.....	a, b, c.....			
California.....	a, b, c.....	a, b.....	a, b, c.....			
Illinois.....	a, b, c.....	a, b, c, d.....	a, b, c.....		Yes.....	
Indiana.....	b, c.....	a, b, c, e.....	b, c.....		Yes.....	
Kansas.....	a, b, c.....	b, c.....	a, c.....			
Maryland.....	a, b, c.....	b, c.....			Yes.....	Yes.....
Michigan.....	a, b, c.....	b, c.....	a.....		Yes.....	
Missouri.....	a, b.....		a, c.....			
North Carolina ²						
North Dakota.....	a.....	b, c, e.....	c.....			a.....
Pennsylvania.....	c.....		c.....	Yes.....	Yes.....	
South Dakota.....	a, b, c.....	b, c.....	c.....			
Texas.....	a, c.....	a, b, d.....	c.....			a, c.....
Utah.....	a, b.....	b, d.....	a.....			
Vermont.....	a.....	a.....	a.....			a, c.....
Virginia ³						

¹ Categories of Federal research:

1. Evaluation:
 - a. Of operational programs.
 - b. Physical studies.
 - c. Extra-area effects.
2. Seeding technology:
 - a. New seeding agents.
 - b. Transport and diffusion, delivery methods.
 - c. Hail suppression methods.
 - d. New tools, for example, satellites.
 - e. Public education.
3. Economic, ecological, and societal studies:
 - a. Economic benefits.
 - b. Toxicity of agents.
 - c. Societal studies.
4. Detection of clandestine seeding.
5. Inadvertent weather modification.
6. Forecasting:
 - a. Short range.
 - b. Local topographic effects.
 - c. Long range.

² Need a national policy first.

³ Mainly hurricane modification.

RESEARCH RECOMMENDATIONS OF THE AMS COMMITTEE ON WEATHER MODIFICATION

Recently, the chairman of the Committee on Weather Modification of the American Meteorological Society ²⁸ summarized his committee's recommendations on recommended weather modification research needs.²⁹ It was noted that the primary focus of such research should be in the areas of purposeful alteration of patterns of cloud systems and precipitation and in the inadvertent impact of man's activities. In view of critical water problems affecting large portions of the country and the potential for increased demand for application of weather modification techniques by water users, the necessity for improved understanding of underlying physical processes through pursuit of basic research was emphasized. In particular, the "real payoff" to improvements in purposeful weather modification should be seen as coming from increased ability to understand, predict, and

²⁸ Weather modification activities of the American Meteorological Society and purposes and concerns of its Committee on Weather Modification are discussed in ch. 8, p. 395.

²⁹ Silverman, Bernard A., testimony before the U.S. Department of Commerce Weather Modification Advisory Board, Champaign, Ill., Oct. 14, 1977.

control the formation and development of mesoscale³⁰ cloud systems.³¹

Subject areas for recommended research to accomplish basic understanding of atmospheric processes necessary for the development of weather modification technology were presented by the AMS committee in the following outline form:³²

Mesoscale Cloud Dynamics

A. Effect of seeding on convective cloud development and evolution:

1. Growth of convective clouds.
2. Merger of clouds into groups and systems.
3. Organization of inflow (coupling of midtroposphere with the boundary layer).
4. Enhanced moisture budget efficiency.

B. Interaction of clouds with each other and with their environment:

1. Response to mesoscale forcing function.
2. Relationship between low-level convergence and cloud field evolution.
3. Role of outdrafts in development and sustenance of cloud systems.
4. Role of anvils in the evolution of the cloud field.

C. Precipitation "nowcasting":

1. Low-level convergence field as predictor of precipitation intensity.
2. Kinematic and thermodynamic predictors and covariates for statistical evaluation.

D. Need for a multidisciplined mesoscale experiment with strong physical emphasis.

Precipitation Microphysics

A. Evolution of natural ice in cloud:

1. Nucleation processes.
2. Secondary ice production processes:
 - (a) Laboratory studies of causality.
 - (b) Field investigations to define appropriate in-cloud criteria for multiplication of ice.

B. Interaction between microphysics and dynamics to produce and sustain precipitation.

C. Effect of seeding on (A) and (B) above.

D. Distinction between microstructure of clouds developing over land and over water in terms of suitability for seeding.

E. Clarification of microstructure of clouds developing within the hurricane environment in terms of suitability for seeding.

F. Cloud microstructure climatology for selected regions of the United States.

G. Effect of ice generation on charge separation and electrification.

³⁰ Mesoscale meteorological phenomena are those with horizontal dimensions ranging from a few tens of kilometers to a few hundred kilometers.

³¹ Silverman, testimony before Weather Modification Advisory Board, 1977.

³² *Ibid.*

Area of Seeding Effect

- A. Induced by dynamic response of environment.
- B. Induced by diffusion of nucleating material :
 - 1. In orographic regions.
 - 2. Transport through convective processes.
- C. Insolation pattern resulting from mid- and upper-level outflow.

Turbulence and Diffusion

- A. Targeting of surface-based source(s) of nuclei into desired cloud region.
- B. Entrainment processes related to cloud development.
- C. Spread of nuclei released in cloud (spatial and temporal distribution).

Seeding Agents and Methods

- A. Nucleation efficiency studies.
- B. Particle sizing and composition analyses.
- C. Particle generation systems.
- D. Improvement of technology.

Cloud Climatology for Technology Applicability

- A. National in scope.
- B. Frequency of occurrence of clouds by type.
- C. Cloud base and cloud top heights for selected regions.
- D. Properties of in-cloud microstructure.
- E. Aerosol characteristics.
- F. Radar population studies.
- G. Precipitation statistics.
- H. Model-derived "seedability" assessment.

Inadvertent Impacts

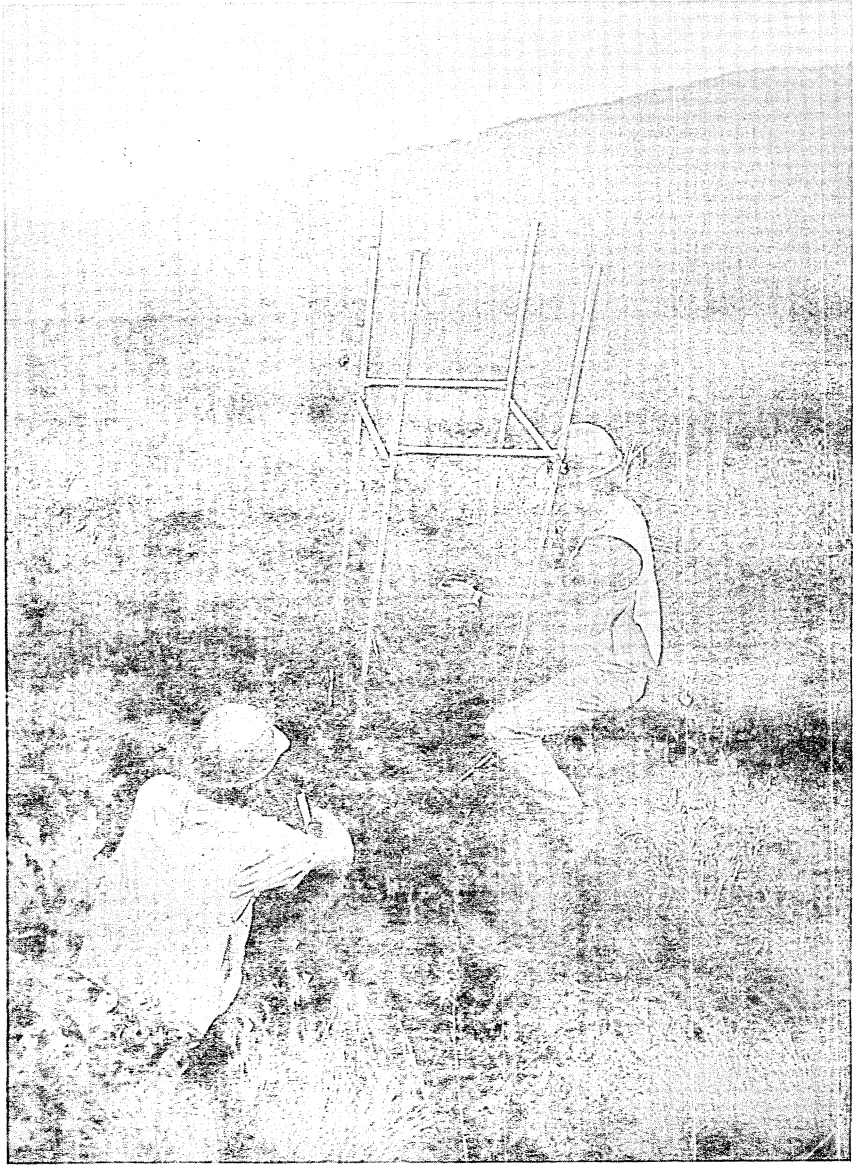
- A. Effect on climatic change.
- B. Effect on air quality.
- C. Effect on meteorology near large urban regions :
 - 1. Thermal pattern.
 - 2. Precipitation.
 - 3. Cloudiness.
- D. Effect on meteorology near deforested areas.

Cloud Modeling

- A. Synthesis of numerical simulation with atmospheric observations on all scales.
- B. Inclusion of cloud interaction and outdraft convergence.
- C. Mesoscale forcing (e.g. sea breeze, topography, etc.).

Improved Methods of Statistical Design and Evaluation

- A. Required to interpret results of new mesoscale experiment.
- B. Required for extraction of physical information from previously-performed nonrandomized experiments.



Study of oak brush as elk forage—part of environmental research conducted as part of Project Skywater. (Courtesy of the Bureau of Reclamation.)

RESEARCH RECOMMENDATIONS RELATED TO EXTENDED AREA AND TIME EFFECTS

At the 1977 workshop on the extended area and extended time effects of weather modification, participants developed some recommendations for future research into these effects.³³ The following research activities, not necessarily in any order of priority, were recommended to be undertaken immediately with current available tools or over a period of time, as appropriate:

The use of computer simulation and modeling can provide important information on the areal coverage and magnitude of the effects of weather modification. It can also define the types of information and the sensitivity required for future field experiments.

Models developed to detect moisture depletion in natural and seeded cases as an airmass moves over successive mountain ridges should be applied and verified by field measurements in an area with a minimum of complexities caused by the introduction of new moisture sources. In situ measurements of temperature, pressure, liquid water content, ice crystal concentrations, and precipitation on the ground and in the air will be needed as inputs to the model and for model validation.

An intensive study should be initiated on particulate transport, including the transport of both seeding material and ice crystals produced by seeding. Techniques are currently available to measure ice crystal concentrations, nuclei, and silver in precipitation. Special tracers are becoming available and should be developed further. Remote sensing techniques for measuring ice and water need further development.

A re-analysis of some past field programs could be undertaken immediately. (The question of apparent decreases in seeding effectiveness in successive years of the Australian experiment has not been resolved adequately as to whether this effect is real or an analysis artifact. The reported persistence of ice nuclei for days after seeding at Climax and its relationship to the apparent decrease in the seed/no seed ratios with time should be further investigated.)

Continuing monitoring should be initiated of such quantities as ice nuclei concentrations in project areas in order to establish new benchmarks. A modeling effort should also be undertaken to investigate the evaporation and reprecipitation processes.

Studies of wide-area effects from seeding summer convective storm systems may require more preliminary work before mounting a major field effort since less is known about these phenomena. These studies should be directed toward acquiring information about the possible redistribution of convective instability and the microphysical effects including the transport of ice nuclei and/or ice crystals, and the possible interactive effects when these particles are entrained into other cloud systems.

Prior to the design of a major wide-area study program, initial studies should include: cloud population studies, including time

³³ Brown, et al., "Transactions of the Workshop on Extended Space and Time Effects of Weather Modification," 1978, pp. 14-18.

and space distributions and cloud microphysics; hypothesis development, including numerical modeling; reexamination of previous experimental programs; augmentation of ongoing programs to study total-area effects; and development of new capabilities including satellite measurements, rain gage network design, data processing, and management and seeding delivery systems.

The final design of a field program will be dependent on the findings from these preliminary studies. It appears likely that it will be necessary to mount a major effort to determine the total-area effects and mechanics of convective storm seeding. Preliminary estimates call for a 10-year study covering an area of at least a 300-mile radius in the mid-United States. Ideally this study could be operated in conjunction with other mesoscale field studies in cumulus convection and precipitation forecasting.

A national technology assessment on precipitation modification should be conducted with the total-area effect included in both the physical science and social science context.³⁴

³⁴ Ibid.

CHAPTER 4

INADVERTENT WEATHER AND CLIMATE MODIFICATION

(By John R. Justus, Analyst in Earth Science, Science Policy Research Division,
Congressional Research Service)

Out of the total ensemble of environmental factors, the subset which is sensed most immediately and directly by man and which has the greatest integrated impact on human activities is that which is subsumed under the terms of weather and climate.—Earl W. Barrett, 1975, National Oceanic and Atmospheric Administration.

INTRODUCTION

The relationship between man and weather has been basically the one stated succinctly by Charles Dudley Warner: Everybody talked about the weather, but nobody did anything about it. In the 1940's, however, the discovery that clouds could be modified by additions of freezing nuclei created a realization that, at some times and places at least, it might be possible to do something about the weather. This entering wedge into the field of intentional or planned weather modification has since been heavily studied and exploited; it had, as a by-product, the creation of considerable interest in weather modification on the part of both the scientific community and the general population. The science and technology of planned weather modification are discussed in chapter 3. The possibility that man has, in fact, been doing something about the weather without knowing it has become a subject for serious consideration, and chapter 4 reviews a number of processes and mechanisms governing inadvertent weather and climate modification.

TERMINOLOGY

By way of clarification, it is important to appreciate the fact that differences of scale are implied in the terms "weather modification" and "climate modification."

Climate

To most everyone, the term climate usually brings to mind an average regime of weather or the average temperature and precipitation of a locality. This is a rather misleading concept, for the average may be a rare event. Actually, weather from year to year oscillates widely so that climate is a statistical complex of many values and variables, including the temperature of the air, water, ice, and land surfaces; winds and ocean currents; the air's moisture or humidity; the cloudiness and cloud water content, groundwater, lake levels, and the water content of snow and of land and sea ice; the pressure and density of

the atmosphere and ocean; the composition of (dry) air; and the salinity of the ocean. All of these elements encompass climate and are interconnected by the various physical and dynamic processes occurring in the system, such as precipitation and evaporation, radiation, and the transfer of heat and momentum by advection (predominantly horizontal, large-scale motions of the atmosphere), convection (large-scale vertical motions of the atmosphere characterized by rising and sinking air movements), and turbulence (a state of atmospheric flow typified by irregular, random air movements).

Climatic fluctuation and climatic change

Rather than by average value, these elements are best characterized by frequency distributions, which can, in many places, span a wide range for a given element. Within such a range, one notes irregular fluctuations characterized by the occurrence of extreme values for given elements of the climatic system. In such instances, a climatic fluctuation is said to be experienced, not a climatic change. A change denotes that a new equilibrium had been achieved, and with it, a rather different frequency distribution for all climatic elements. Thus, the term change is not to be confused with fluctuation, where trends are frequently reversed, even though some successive values may cluster for a while on one side or the other of the "average."

Weather

Defined as the state of the atmosphere at any given time, the prevalent belief of the public, that wherever the weather goes the climate follows, is fallacious. On the contrary, wherever the climate goes, so goes the weather. Weather is merely a statistic of the physical climatic state.

Weather modification

As used in the context of this chapter and in the text at large, weather modification refers collectively to any number of activities conducted to intentionally or inadvertently modify, through artificial means, the elements of weather and, in turn, the occurrence and behavior of discrete weather events. Intentional or planned weather modification activities may be conducted for a variety of different purposes, including: Increasing or decreasing rain and snow over a particular area; reducing damage to crops and property from hail; reducing the number of forest fires that are started by lightning; removing fog at airports; changing the intensity and direction of hurricanes so they cause less destruction; mitigating the destructiveness of severe thunderstorms and tornadoes.

Climate modification

This encompasses the planned or inadvertent alteration, through artificial means, of the elemental properties comprising the air, sea, ice, land, and biospheric components of the climatic system in order to effect a new equilibrium among the elements of climate and, consequently, a new climate regime. In most instances, the term alludes to mesoscale and macroscale climates, from those of regions to the entire globe. Another common usage is in reference to the microscale climates of cities where persistent, inadvertent effects on weather, in turn, modify the climates of greater metropolitan areas.

Planned climate modification

While the term climate usually brings to mind an "average" regime of weather or, more properly, a frequency distribution of the elements and events of weather, the climatic system itself consists of those elements and processes that are basically the same as those responsible for short-term weather and coordinately for the maintenance of the long-term physical climatic state. It follows, then, that one of the purposes of planned weather modification activities may be to artificially change the climate of a location or region through means including, but not necessarily limited to: Massive and protracted extension of present cloud-seeding operations to influence natural precipitation development cycles; intentional initiation of large heat sources to influence convective circulation or evaporate fog; intentional modification of solar radiation exchange or heat balance of the Earth or clouds through the release of gases, dusts, liquids, or aerosols in the atmosphere; planned modification of the energy transfer characteristics of the Earth's land or water surface by dusting with powders, liquid sprays or dyes, water impoundment, deforestation, etc.

The dramatic idea of some great technological leap toward purposefully altering climate never seems to lose its appeal. The problem with these grand schemes is that, even if feasible, every fix—technological or otherwise—has its toll in side effects. But leaving aside for the moment the question of whether it makes sense to alter or conserve climate, many of the schemes that have been suggested for modifying climate on a hemispheric or global scale have so far been considered to be on the fringe of science fiction. The range of possibilities widens rapidly if one imagines the financial resources of the major world powers available to carry them out. Periodically resurgent are such schemes as darkening, heating, and melting of the Arctic icepack, the damming of the Bering Strait, the transportation of Antarctic icebergs, the diverting southward of North American and Asian rivers that empty into the Arctic, and the modification of tropical storms.¹ These and other perennial suggestions are summarized in Figure 1.

¹ Kellogg, W. W. and S. H. Schneider, "Climate Stabilization: For Better or for Worse?" *Science*, vol. 186, Dec. 27, 1974, pp. 1163-1172.

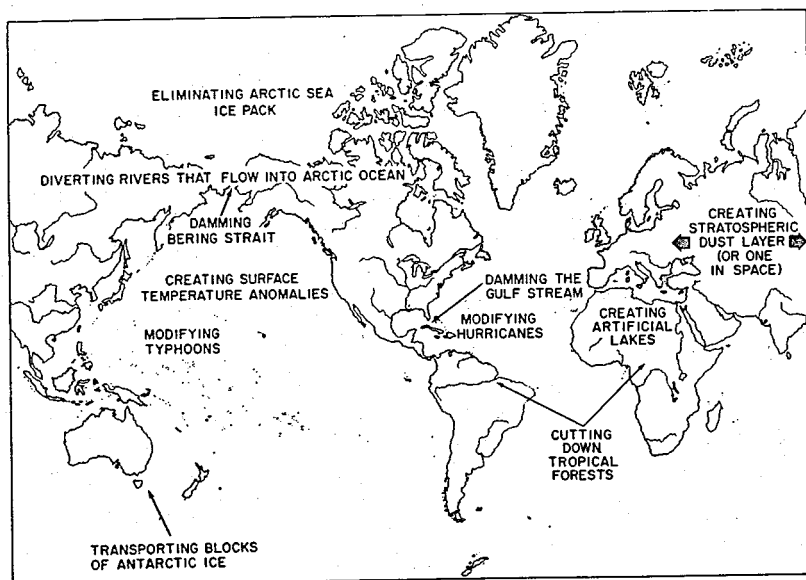


FIGURE 1.—A survey of grandiose schemes that have been proposed to modify or control climate. (From Kellogg and Schneider, 1974.)

Inadvertent climate modification

The modification processes may also be initiated or triggered inadvertently rather than purposefully, and the possibility exists that society may be changing the climate through its own actions by pushing on certain leverage points. Inadvertently, we are already causing measurable variations on the local scale. Artificial climatic effects have been observed and documented on local and regional scales, particularly in and downwind of heavily populated industrial areas where waste heat, particulate pollution and altered ground surface characteristics are primarily responsible for the perceived climate modification. The climate in and near large cities, for example, is warmer, the daily range of temperature is less, and annual precipitation is greater than if the cities had never been built. The climate of the world is governed mainly by the globally averaged effects of the Sun, the location and movement of air masses, and the circulation patterns of the world ocean. It is by no means clear that the interaction of these vast forces can be significantly influenced by human activities. Although not verifiable at present, the time may not be far off when human activities will result in measurable large-scale changes in weather and climate of more than passing significance. It is important to appreciate the fact that the role of man at this global level is still controversial, and existing models of the general circulation are not yet capable of testing the effects in a conclusive manner.

Nevertheless, a growing fraction of current evidence does point to the possibility of unprecedented impact on the global climate by human activities, albeit the effects may be occurring below the threshold where they could be statistically detected relative to the record

of natural fluctuations and, therefore, could be almost imperceptible amid the ubiquitous variability of climate. But while the degree of influence on world climate may as yet be too small to detect against the background of natural variations and although mathematical models of climatic change are still imperfect, significant global effects in the future are inferred if the rates of growth of industry and population persist.

BACKGROUND

HISTORICAL PERSPECTIVE

The possibility of climatic alterations by human activity was alluded to in the scientific literature at the beginning of this century, and again in the late 1930's, but it received little serious attention until the 1950's. The first period of thermonuclear testing, 1954 to 1958, generated a great deal of concern about drastic and widespread effects on weather. It was felt that anything which liberated such great energies must somehow influence the atmosphere. The fact that a device fired at sea level or under the sea did create locally a large convective cloud was cited as evidence.

By about 1960 work had shown that no large-scale or long-term meteorological effects would ensue from nuclear testing at the levels conducted in the 1950's. It had become clear that the inertia of the atmosphere-ocean system was too large to be perturbed seriously by the sudden release of any energy man could generate. Instead of the spectacular and violent, it was realized that one would have to look to the slow and insidious to find evidence of human influences on climate and weather.

Some evidence that manmade carbon dioxide was accumulating in the atmosphere appeared as early as 1938. This, together with some early systematic data from Scandinavia, led to the inclusion of a carbon dioxide (CO_2) measurement program during the International Geophysical Year (IGY), 1957-1958. This CO_2 measurement program, which continues today, was the first serious scientific study of a possible manmade climatic influence on a large scale.

As the reality of the CO_2 effect became established, and as the general mood of increased concern for the environment and the concept of "spaceship Earth" developed during the 1960's, increased scientific efforts began to be focused on inadvertent weather and climate modification. It had been recognized for some time that the climates of cities differed significantly from their rural environs due to the release of heat and pollutants. It was not until the late 1960's that evidence of "urban effect" on the climate at considerable distances downwind began to be noticed. The role of pollution aerosols² as climate modifiers became a topic of great interest, and it remains so today.

In the United States, the attention of the Government to these problems began with the IGY effort. CO_2 and solar radiation measurement programs were started in Antarctica and at the Mauna Loa Observatory in Hawaii, which was established specifically for this program by the U.S. Weather Bureau. This station, located at an elevation of 3,400 meters (11,155 feet) on the north slope of Mauna Loa,

² Dispersions in the atmosphere of particles of matter that remain suspended for a significant length of time.

has been improved over the years and remains the prototype "benchmark" station for climatic change monitoring.

The first major meeting devoted exclusively to the inadvertent modification problem convened in Dallas, Tex., in December 1968.³

The following year, a series of discussions between some faculty members of the Massachusetts Institute of Technology, government officials and scientists gave rise to the first working conference, the Study of Critical Environmental Problems (SCEP). This meeting, held at Williams College, Williamstown, Mass., during July 1970, was devoted to identifying possible global environmental hazards and making recommendations concerning monitoring, abatement, et cetera. The climatic problem areas identified were carbon dioxide and other trace gases that may affect climate; particulate matter in the atmosphere as turbidity and as cloud modifiers; waste heat; changes in the Earth's surface (land-use changes); radioactivity in the atmosphere; and jet aircraft pollution of the high troposphere and stratosphere. The proceedings of this meeting were published by the MIT Press.^{4, 5}

The working group for SCEP was, with one exception, composed of residents of the United States: scientists, representatives of industrial management, and government officials. Some of the participants felt that a more multinational participation would be essential if standardized global programs were to come into existence as a result of such a meeting. Also, it was the opinion that the problems of climate modification were complex enough to occupy the entire attention of a working meeting. As a result, a second such meeting was held, this time in Stockholm, with scientists from 14 countries participating. This working meeting was called Study of Man's Impact on Climate (SMIC). The report prepared by this group⁶ dealt with the substantive scientific questions of inadvertent climate modification, including: previous climatic changes; man's activities influencing climate; theory and models of climatic change; climatic effects of manmade surface changes; modification of the troposphere;⁷ and modification of the stratosphere.⁸ One objective of SMIC was to provide guidelines for the World Meteorological Organization (WMO) and other international agencies to use in establishing monitoring and research programs on a global scale.

In connection with the study of inadvertent climate modification, much was iterated in the early 1970's about the need for global monitoring. Because of the lagtime in planning, financing, and constructing such facilities (which must necessarily be in wilderness areas in order to give representative data not reflecting local effects), the minimum number of benchmark stations (10) considered necessary has not yet been reached. Five stations are currently in operation. Mauna Loa Observatory (MLO), the oldest, was established by the

³ Singer, S. F., "Global Effects of Environmental Pollution," New York, Springer-Verlag, 1970.

⁴ Wilson, Carroll L., editor. *Man's Impact on the Global Environment, Report of the Study of Critical Environmental Problems (SCEP)*. Cambridge, MIT Press, 1970, 319 pp.

⁵ Matthews, W. H., W. W. Kellogg, and G. D. Robinson, editors. "Man's Impact on the Climate." Cambridge, MIT Press, 1971, 594 pp.

⁶ Wilson, C. L., and W. H. Matthews, editors. *Inadvertent Climate Modification, Report of the Study of Man's Impact on Climate (SMIC)*. Cambridge, the MIT Press, 1971, 308 pp.

⁷ Troposphere—the inner layer of the atmosphere varying in height from 6 to 12 miles. This is the region within which nearly all weather conditions manifest themselves.

⁸ Stratosphere—the region of the atmosphere outside the troposphere, about 10 to 30 miles in height.

U.S. Weather Bureau, then transferred to the supervision of the Atmospheric Physics and Chemistry Laboratory of the Environmental Science Services Administration in 1966 and finally to the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (NOAA) in 1971. In the following year, the NOAA network was officially expanded to four stations: MLO; South Pole; Point Barrow, Alaska; and American Samoa. The other operational station is located at Kislovodsk, North Caucasus, in the U.S.S.R. The Government of Canada has plans for three high latitude northern stations, and some limited monitoring activities are conducted in Australia and New Zealand.

In addition to the long-term monitoring program, two shorter programs have been devoted to the inadvertent modification problem. The first of these, the Metropolitan Meteorological Experiment (Metromex), was directed toward a concentrated investigation of downwind effects of the thermal and particulate emissions from a typical metropolitan area—St. Louis, Mo. The project involved an examination of all available climatological data in a circle around the city, plus an extensive field program in which a number of State and Federal Government agencies and university research groups participated.

The objective of the second program was to prepare an environmental impact statement on the effects of supersonic transport aircraft. The resulting research activity, the Climatic Impact Assessment Program (CIAP), involved 9 agencies and departments of the Federal Government, 7 agencies of other national governments, and over 1,000 individual scientists in the United States and abroad. The program involved data-collecting activities using aircraft and balloons in the stratosphere, development of new techniques for sampling and measuring stratospheric pollutants, laboratory work in the photochemistry of atmospheric trace gases, measurement of pollutant emission by aircraft engines, mathematical modeling of stratospheric transport processes and chemical reactions taking place there.⁹

UNDERSTANDING THE CAUSES OF CLIMATIC CHANGE AND VARIABILITY

It is a human tendency to cling to the belief that the natural environment or climate to which we have become accustomed will remain more or less the same from year to year and from decade to decade. We are surprised and alarmed when an unusually severe winter or an unusually prolonged drought occurs, because our memories tend to be too short to recall past years when things were equally unusual.

—William W. Kellogg, 1978
National Center for Atmospheric Research.

The facts are that climate everywhere does fluctuate quite noticeably from year to year and that there are gradual changes in climate that make one decade or one century different from the one before. These yearly fluctuations and longer term changes have been the result of natural processes or external influences at work on the complex system that determines Earth's climate. It is a system that seems to strive for a balance among atmosphere, oceans, land, and polar ice masses—all

⁹ Barrett, Earl W., "Inadvertent Weather and Climate Modification." Critical Reviews in Environmental Control, vol. 6, No. 1, December 1975, pp. 15-90.

influenced by possible solar and cosmic variations of which climate researchers' knowledge is in some cases nonexistent, or incomplete, and otherwise tenuous at best. Society itself is becoming another significant factor in the climatic balance.

It is no news, for example, that the atmosphere of large midlatitude cities is both warmer and more turbid than the surrounding countryside (particularly in winter) as a result of thermal and chemical pollution and to some extent because of the ability of groups of buildings to trap heat from the Sun. There is also good evidence for increased summertime rainfall downwind from cities such as St. Louis, Chicago, and Paris.¹⁰ Indeed, it is very likely that the industrialization of sizable regions, such as the eastern United States and western Europe, has modified their climates in certain more subtle ways. In any attempt to assess a manmade climatic effect, it is essential to understand and have a measure of the degree of climatic variability which may be expected in the absence of human influence.

The concept of climatic change and variability

The concept of climatic change and variability entails a wide range of complex interactions with a disparity of response times among the air, sea, ice, land, and biotic components of the climate system. Climate is not a fixed element of the natural environment. Indeed, important advances in climate research and the study of former climates confirm that past climates of Earth have changed on virtually all resolvable time scales. This characteristic suggests that there is no reason to assume the favorable climatic regime of the last several decades is permanent and, moreover, that climatic change and variability must be recognized and dealt with as a fundamental property of climate.

In this matter it is important to appreciate the fact that a renewed appreciation of the inherent variability of climate has manifested itself in the public consciousness. Climate has not become suddenly more variable in a way that it has never been variable before, but events of recent years¹¹ have shaken a somewhat false sense of technological invulnerability. Thus, climatic variability is a media item now because society ignored for so long its continued dependence on the ecological/climatic balance achieved, and then failed to plan systematically for the coming unfavorable years, which eventually had to come—and always will, given the nature of the atmosphere. It is more palatable to blame climate for present predicaments than to acquiesce to a lack of preparedness. As F. Kenneth Hare, climatologist with the Science Council of Canada, has noted:

It is paramount that the [climate-related] events of 1972 do not repeat themselves, even if bad weather does. It does not matter whether such events are part of a genuine change in climate or are merely unusually large fluctuations of a basically unchanging system. In fact, I doubt whether such arguments mean anything. It does matter that climatic extremes do occur; that they have recently become rather frequent and have had severe impacts; that we lack the predic-

¹⁰ Dettwiller, J. W. and S. A. Changnon, "Possible Urban Effects on Maximum Daily Rainfall Rates at Paris, St. Louis, and Chicago." *Journal of Applied Meteorology*, vol. 15, May 1976, pp. 517-519.

¹¹ Most of the world's important grain-growing regions experienced unfavorable weather and crop failures in 1972 or 1974, or both. The winter of 1977 was perceived by most Americans as remarkably abnormal, with severe cold in the East (coldest, in fact, since the founding of the Republic), drought in the West, and mild temperatures as far north as Alaska: and the summer of 1977 was one of the two or three hottest in the last 100 years over most of the United States.

tive skill to avoid impacts on food production—and energy consumption; and that we [the atmospheric science community] are insufficiently organized to make maximum use of existing skill.¹²

While scientists concur that climate is not a fixed component of the natural environment, there is less agreement with regard to when and how climatic change occurs. Although in the long term a major natural change to a different climatic regime may be expected, it is unlikely that any trend toward such a change would be perceptible in the near term, as it could be obscured by large amplitude, shorter term climatic variability. Considered from a historical perspective, and judging from the record of past interglacial ages, climatic data indicate that the long-term trend over the next 20,000 or so years is toward a cooling cycle, a cooler climate, and eventually the next glacial age. The onset of that change may be a number of centuries or millennia away; conceivably it may already have begun. In recent years, books and newspaper stories have conditioned us to expect colder weather in the future. In geological perspective, the case for cooling is strong. The modern-day world is experiencing an interglacial period, a relatively warm interlude—lasting many thousands of years—between longer intervals of cold. If this interglacial age lasts no longer than a dozen earlier ones in the past million years, as recorded in deep-sea sediments, we may reasonably suppose that the world is about due to begin a slide into the next ice age. It does seem probable, though, that this transition would be sufficiently gradual so that in the next 100 to 200 years it would be almost imperceptible amid the ubiquitous variability of climate.^{13, 14, 15}

Considering the much more recent past, climatologists point out that the world has been in the throes of a general cooling trend during the last 30 or 40 years. Because this modern-day cooling trend has sometimes been misinterpreted as an early sign of the approach of an ice age (it really is only one of many irregular ups and downs of climate that mankind has witnessed through history), it has reinforced the popular notion that our future is likely to be a cold one. (In point of fact, this cooling trend has been faltering in very recent years, and may already have started to reverse itself.)

Writes research climatologist J. Murray Mitchell, Jr.:

I agree with those climatologists who say that another ice age is inevitable. I strongly disagree, however, with those who suggest that the arrival of the next ice age is imminent, and who speak of this as the proper concern of modern civilization in planning for the next few decades or centuries. Should nature be left to her own devices, without interference from man, I feel confident in predicting that future climate would alternately warm and cool many times before shifting with any real authority toward the next ice age. It would be these alternate warmings and coolings, together with more of the same ubiquitous, year-to-year variability of climate that has always been with us, that would be the appropriate object of our concerns about climate in the foreseeable future.¹⁶

¹² Norwine, Jim, "A Question of Climate," *Environment*, vol. 19, No. 8, November 1977, p. 12.

¹³ National Research Council, U.S. Committee for the Global Atmospheric Research Program, *Understanding Climatic Change: A Program for Action*, Washington, National Academy of Sciences, 1975, 239 pp.

¹⁴ U.S. Federal Council for Science and Technology, Interdepartmental Committee for Atmospheric Sciences, report of the Ad Hoc Panel on the Present Interglacial, Washington, National Science Foundation, 1974, 22 pp. (JCAS 18b-FY75).

¹⁵ United Nations, World Meteorological Organizations (WMO), WMO Statement on Climatic Change, pt. B: technical report, p. 9.

¹⁶ Mitchell, J. Murray, Jr., "Carbon Dioxide and Future Climate," *EDS [Environmental Data Service] magazine*, March 1977, p. 4.

Because of man's presence on the Earth, however, what will actually happen in future decades and centuries may well follow a different scenario; imperceptibly different at first, but significantly so later on, covering a full spectrum of climatic possibilities ranging from warming to cooling trends. Varying interpretations of this evidence have led, on one hand, to a scientifically valid caution regarding possible instability of present-day climate conditions and, on the other hand, to predictions that the Earth may be on the verge of a new climate regime, which implies a new equilibrium among the elements of the climatic system, involving a somewhat different set of constraints and, almost certainly, noticeable regional shifts of climate. Climate researchers iteratively emphasize the importance of recognizing and appreciating the inherent variability of climate, a fact which may be more significant than the uncertainty of whether recent events portend a trend toward a warmer or cooler climate of the future.

When and how do climatic changes occur?

So far, there is no single comprehensive theory, or even a combination of a small number of theories, that completely explains—much less predicts—climatic fluctuations or change. As yet, there is no deterministic, predictive model of our planet's climate, and, until one is developed, predictions are as valid as the logic producing them. The periods of time involved in climatic predictions cover centuries, and the validity of climate forecasting is not easily tested. Nevertheless, there are some factors and processes that clearly should be taken into account, either in terms of observed correlations in the past or of theoretical assumptions about what should be important. All, in one way or another, effect changes and variability of climate by modifying the natural thermal balance of the atmosphere.

One group of processes responsible for climatic change and variability consists of external mechanisms, including: fluctuations of the Sun's radiative output, variations of Earth's orbital parameters, changes in atmospheric dust content, changes in levels of carbon dioxide and ozone in the atmosphere, and migration of land masses and shifting of continental plates.

In addition to being influenced by external forcing mechanisms, climate is, to a certain degree, regulated by processes internal to the climatic system, involving "feedback" interactions between the atmosphere, the world ocean, the ice masses, the land surface, and the biosphere. If an external variable were to be changed by a certain factor, the response of the climatic system to that change could be modified by the actions of these internal processes which act as feedbacks on the climatic system modifying its evolution. There are some feedbacks which are stabilizing, and some which are destabilizing; that is, they may intensify deviations.

In all likelihood, climatic change is a function of various combinations of interacting physical factors, external processes, internal processes, and synergistic associations (see fig. 2), but it is not yet clear to what extent the observed variability of the climatic system originates from internal mechanisms, and to what extent from external mechanisms. It appears likely that the answer depends upon the time scale of variability, with internal processes probably important on the scale of months and decades, and external mechanisms becoming increasingly important on time scales beyond a century as depicted in figure 3.

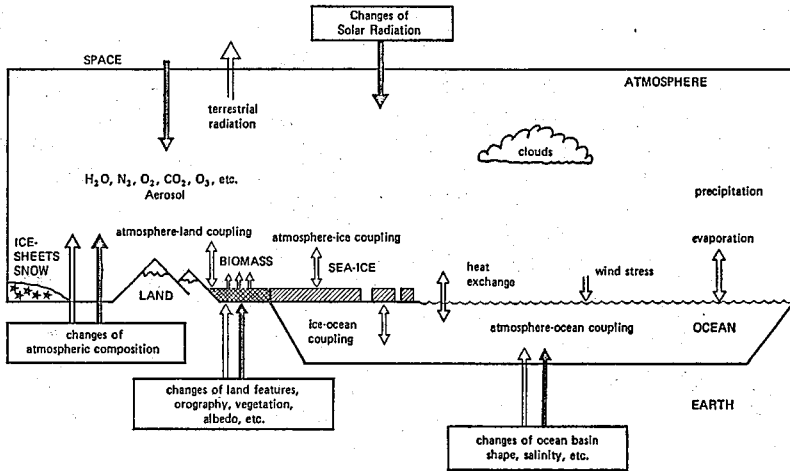


FIGURE 2.—Schematic illustration of the components of the coupled atmosphere-ocean-ice-land surface-biota climatic system. The full arrows are examples of external mechanisms, and the open arrows are examples of internal mechanisms of climatic change.

Source: Living With Climatic Change. Proceedings of a conference/workshop held in Toronto, November 17–22, 1975. Ottawa, Science Council of Canada, 1976, p. 85.

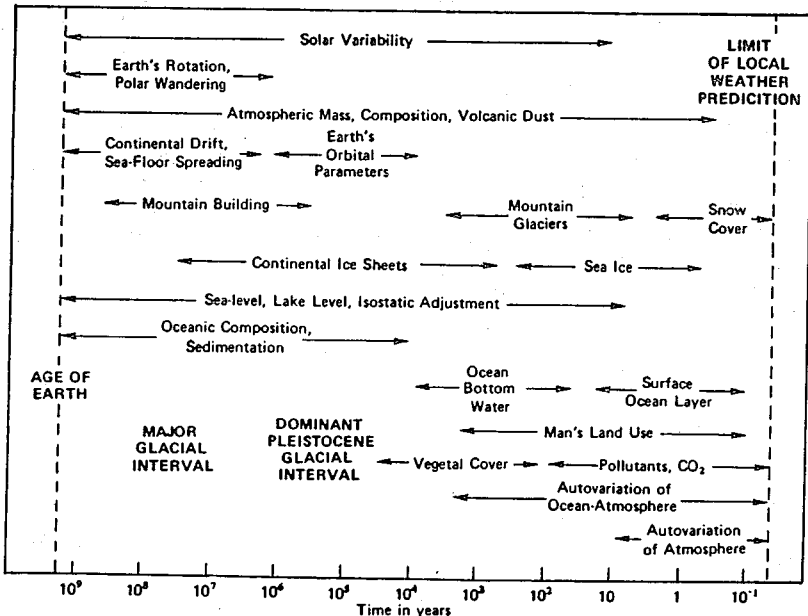


FIGURE 3.—Characteristic climatic events and processes in the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere and possible causative factors of global climatic change.

Source: National Research Council, U.S. Committee for the Global Atmospheric Research Program. Understanding Climatic Change: A Program for Action. Washington, National Academy of Sciences, 1975, p. 22.

For a comprehensive and detailed discussion of the mechanisms and factors governing climatic change and variability, see "A Primer on Climatic Variation and Change" (1976).¹⁷

The possibility also exists that society may be changing the climate through its own actions by pushing on certain leverage points. Our presence on Earth cannot be assumed to go unnoticed by the atmosphere, and human intervention now presents possibilities that have never existed in the historic or geologic past. At question is whether the effects of civilized existence are yet capable of altering Earth's heat balance and, hence, impacting climate on a global scale to an important extent. Enormous amounts of gaseous and particulate materials have been emitted into the atmosphere through the combustion of fossil fuels (primarily carbon dioxide, sulfur dioxide, and fly ash) and through the manipulation of land for agriculture and commerce (primarily windblown dust, and forest and grass fire smoke). To an increasing extent, waste heat is also entering the atmosphere, both directly and indirectly (via rivers and estuaries) and in both sensible and latent form (as, for example, through evaporation in wet cooling towers). Moreover, large-scale land management programs have been responsible for significant changes in reflective properties, moisture holding capacity, and aerodynamic roughness of the surface (primarily through deforestation, water impoundment by manmade lakes, slash-burn agriculture practices, urbanization, and so forth). In view of the growth of population, industry, food production, and commerce in the years and decades ahead, the time is almost certainly not far off when human effects on large-scale climate would become appreciable in relation to natural phenomena leading to changes and variability of climate.

It does seem likely that industrial man already has started to have an impact on global climate, although this is difficult to prove by direct observation, because the impact is not easily recognizable amid the large natural variability of climate. "If man continues his ever-growing consumption of energy," contends J. Murray Mitchell, "and in the process adds further pollution to the global atmosphere, it may not be very many years or decades before his impact will break through the 'noise level' in the record of natural climatic variability and become clearly recognizable."¹⁸ Furthermore, the most significant impacts that mankind would probably have on the climatic system are apparently all in the same direction as far as global mean temperatures are concerned and are likely to constitute a warming trend.¹⁹

THE FACTS ABOUT INADVERTENT WEATHER AND CLIMATE MODIFICATION

AIRBORNE PARTICULATE MATTER AND ATMOSPHERIC TURBIDITY

Particulate matter in the atmosphere may significantly affect climate by influencing the Earth's radiation balance (figure 4) and/or cloud nucleation and precipitation.

¹⁷ Justus, John R., "Mechanisms and Factors Governing Climatic Variation and Change." In "A Primer on Climatic Variation and Change," prepared by the Congressional Research Service, Library of Congress, for the Subcommittee on the Environment and the Atmosphere of the Committee on Science and Technology, U.S. House of Representatives, 94th Cong., 2d sess. (committee print). Washington, U.S. Government Printing Office, 1976, pp. 77-127.

¹⁸ Mitchell, J. Murray, Jr., "Carbon Dioxide and Future Climate," p. 4.

¹⁹ Kellogg, William W., "Is Mankind Warming the Earth?" Bulletin of the Atomic Scientists, vol. 34, February 1978, pp. 10-19.

Do more particles mean a warming or cooling?

There is a question as to whether more particles mean a warming or cooling of the lower atmosphere. The general cooling trend of the last 30 to 40 years (which some experts feel may have bottomed out and already started to reverse itself) could have been a result of a reduction of solar radiation reaching the surface of the Earth because of particulates that have been scattered into the atmosphere by man's activities, among them: the burning of fossil fuels, mechanized agricultural operations, overgrazing of arid lands, manmade forest fires, and the slash-burn method of clearing land for crops, which is still widely employed in the Tropics. But if man started his polluting processes in the last century, and the decrease of global temperature were due to alteration in the transparency of the atmosphere, then why has a decrease in temperature not been observed earlier? It is possible that instruments were measuring a natural climatic trend that may have been only somewhat augmented by the byproducts of resource development, power generation, and industrial activities.

The situation is such that the net effect of a given particle on Earth's heat balance and hence on climate depends, in large part, upon the nature (number and size) of the particles, where in the atmosphere they are found, and how long they remain suspended. Some aerosols, such as lead from auto exhaust, are rapidly scavenged by precipitation. Others, mostly organic particles such as pesticides, may remain for months or years. While short-term aerosols such as lead may affect weather on a local scale, it is the aerosols that remain and accumulate in the atmosphere that will have long-term effects on climate.

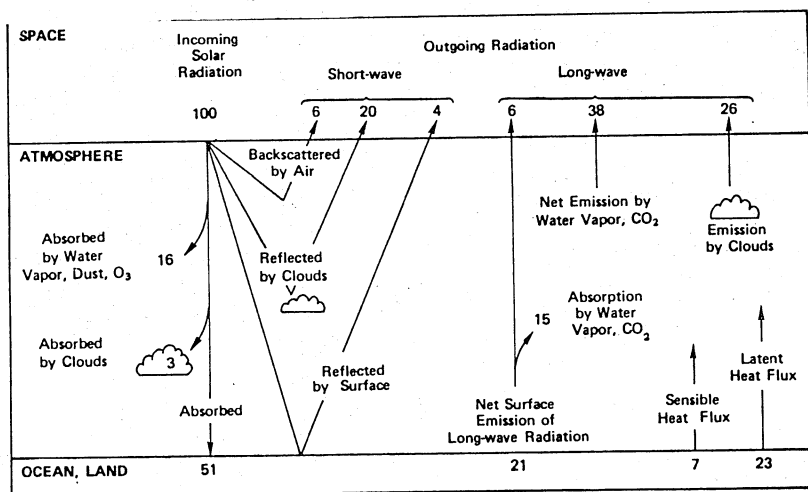


FIGURE 4.—The mean annual radiation and heat balance of the atmosphere, relative to 100 units of incoming solar radiation, based on satellite measurements and conventional observations.

Source: National Research Council. U.S. Committee for the Global Atmospheric Research Program. Understanding Climatic Change: A Program for Action, Washington, National Academy of Sciences, 1975, p. 18.

Idso and Brazel reporting on their research results in the November 18, 1977 issue of Science magazine found that initial increases in atmospheric dust concentration tend to warm the Earth's surface. After a certain critical concentration has been reached, continued dust buildup reduced this warming effect until, at a second critical dust concentration, a cooling trend begins. But, they explain, this second critical dust concentration is so great that any particulate pollution of the lower atmosphere will have the inexorable tendency to increase surface temperatures. The authors pointed out that if, and when, man-generated, industrial pollution of the atmosphere as a source of particulates ever becomes climatologically significant, the resultant surface temperature trend will definitely be one of warming, not cooling. Thus, whereas many groups assigned to assess the problem have looked on this aspect of intensified industrialization as acting as a "brake" on the warming influence inferred lately of increased carbon dioxide production,²⁰ just the opposite is actually the case—the two phenomena could tend to complement each other.²¹

Sources of atmospheric particulates: natural against manmade

Of course, not all aerosols in the Earth's atmosphere, or even a major proportion, are attributable to human activity. In fact, dust from volcanic eruptions, sea salt from evaporated ocean spray, smoke from lightning-caused forest fires (see fig. 5), debris from meteors which burn up in the atmosphere, windblown dust or sandstorms, and organic compounds emitted by vegetation are much larger sources of atmospheric particulates than human activity. Scientists at Stanford University estimate that natural processes produce about 2,312 million tons of aerosols a year, which amount to 88.5 percent of the total. Man and his activities account for only 296 million tons, the remaining 11.5 percent. At present, it is unlikely that man's activities and man-made aerosols will affect global temperatures. It is important to note, however, that while aerosols from natural sources are distributed fairly evenly across the planet, man, in contrast, contributes high concentrations mostly from industrial centers. Atmospheric scientists at the National Oceanic and Atmospheric Administration's Atmospheric Physics and Chemistry Laboratory found that the 296 million tons of manmade aerosols are produced every year on only about 2.5 percent of the surface of the globe. Within these limited areas, manmade aerosols account for nearly 84 percent of the total. It follows, then, that these aerosols may be expected to have noticeable effects on local weather and urban climates.

²⁰ See, generally, National Research Council, Geophysics Research Board, "Energy and Climate," Washington, National Academy of Sciences, 1977, 281 pp.

²¹ Idso, Sherwood B. and Anthony J. Brazel, "Planetary Radiation Balance as a Function of Atmospheric Dust: Climatological Consequences," Science, vol. 198, Nov. 18, 1977, pp. 731-733.



FIGURE 5.—Not all aerosols in the Earth's atmosphere are attributable to human activity. In this Landsat photo, smoke from a fire in the Seney National Forest, upper peninsula of Michigan, serves as a source of atmospheric particulates. Note the extent of the dust veil downwind of the source. (Courtesy of National Aeronautics and Space Administration.)

Atmospheric processes affected by particles

Everyday, particles of soot, smoke, dust, and chemicals from industrial combustion and other activities are emitted into the urban atmosphere. About 80 percent of the solid contaminants are small enough to remain suspended in the air, sometimes for several days.²² Even though these tiny particles reflect and scatter sunlight ostensibly keeping its heat from reaching the ground, they also can act as a lid to prevent the outflow of heat from the land surface to the atmosphere. In a sense, this turbidity acts as an insulator. It reduces the amount of sunlight received at the top of the city in the daytime and cuts down on a source of heat. However, at night urban aerosol pollutants retard the departure of radiant energy from the heated city air, encasing the heat in

²² "Do Cities Change the Weather?" Mosaic, vol. 5, summer 1974, pp. 33, 34.

the city's closed atmospheric system. Certain aerosols may undergo chemical change when they combine with water vapor in the presence of solar radiation. There are many complicated processes that can generate aerosol gas-to-particle conversions, and the particles can then grow by surface chemistry and physical accretion.²³

Perhaps the most sensitive atmospheric processes which can be affected by air pollutants are those involved in the development of clouds and precipitation. The formation and building of clouds over a city can be influenced by the presence of pollutants acting as nuclei upon which water vapor condenses and by the hot dry air with which these aerosols are swept into the base of the clouds (see fig. 6). The structure of clouds with temperatures below 0° C (defined as cold clouds) can be modified, and under certain conditions precipitation from them altered, by particles which are termed ice nuclei.²⁴ The concentrations of natural ice nuclei in the air appear to be very low: Only about one in a billion atmospheric particles which are effective as ice nuclei at temperatures above about -15° C have the potential for modifying the structure of clouds and the development of precipitation. If the concentration of anthropogenic ice nuclei is about 1 in 100 million airborne particles, the result may be an enhancement of precipitation; however, if the concentration is greatly in excess of 1 in 100 million, the result may be a tendency to "overseed" cold clouds and reduce precipitation. Certain steel mills have been identified as sources of ice nuclei. Also of concern is the possibility that emissions from automobiles may combine with trace chemicals in the atmosphere to produce ice nuclei.²⁵

²³ Hobbs, P. V., H. Harrison, E. Robinson, "Atmospheric Effects of Pollutants," *Science*, vol. 183, Mar. 8, 1974, p. 910.

²⁴ National Research Council, Committee on Atmospheric Sciences, "Weather and Climate Modification: Problems and Progress," Washington, National Academy of Sciences, 1973, pp. 41-47.

²⁵ Hobbs, P. V., H. Harrison, E. Robinson, "Atmospheric Effects of Pollutants," p. 910.



FIGURE 6.—The formation and building of clouds can be influenced by the presence of pollutants acting as nuclei upon which water vapor condenses and by the hot dry air with which these aerosols are swept aloft. In this Landsat photo, excess particles as well as heat and moisture produced by the industries of Gary, Ind., favor the development of clouds downwind. The body of water shown is the southern tip of Lake Michigan. (Courtesy of National Aeronautics and Space Administration.)

Precipitation from clouds that have temperatures above 0°C (warm clouds) may be modified by particles which serve as cloud condensation nuclei (CCN). A source that produces comparatively low concentrations of very efficient CCN will tend to increase precipitation from warm clouds, whereas one that produces large concentrations of somewhat less efficient CCN might decrease precipitation. Modifications in the structure of clouds and precipitation have been observed

many miles downwind of fires and pulp and paper mills. Large wood-waste burners and aluminum smelters have also been identified as major sources of CCN.²⁶

The La Porte weather anomaly: urban climate modification

La Porte, Ind., is located east of major steelmills and other industries south of Chicago. Analysis of La Porte records revealed that, since 1925, La Porte had shown a precipitation increase of between 30 and 40 percent. Between 1951 and 1965, La Porte had 31 percent more precipitation, 38 percent more thunderstorms, and 246 percent more hail days than nearby weather stations in Illinois, Indiana, and Michigan.²⁷ Reporting on this anomaly at a national meeting of the American Meteorological Society in 1968, Stanley Changnon, a climatologist with the Illinois State Water Survey pointed out that the precipitation increase in La Porte closely followed the upward curve of iron and steel production at Chicago and Gary, Ind. Furthermore, La Porte's runs of bad weather correlated closely with periods when Chicago's air pollution was bad. Stated simply, Changnon's theory was that if this effect did not occur by chance, then the increase in precipitation could be caused by the excess particles as well as heat and moisture produced by the industries upwind of La Porte. Pollutants from the industrial sources, it seemed, were serving as nuclei to trigger precipitation, just as silver iodide crystals are used to seed clouds in deliberate efforts of weather modification.²⁸

The discovery of the La Porte anomaly helped usher in considerable scientific and public concern as to whether cities could measurably alter precipitation and severe weather in and downwind of them. A large urban-industrial center is a potential source of many conditions needed to produce rainfall. These include its release of additional heat (through combustion and from "storage" in surfaces and buildings) which lifts the air; the mechanical mixing due to the "mountain effects" of a city existing in flat terrain; additional moisture released through cooling towers and other industrial processes; and the addition of many small particles (aerosols), which could serve as nuclei for the formation of cloud droplets and raindrops.

The interest in whether urban emissions into the atmosphere could trigger changes in weather and climate on a scale much larger than the city itself led to climatological studies of other cities. Historical data for 1901-70 from Chicago, St. Louis, Washington, D.C., Cleveland, New Orleans, Houston, Indianapolis, and Tulsa were studied in an effort to discern whether cities of other sizes, different industrial bases, and varying climatic-physiographic areas also experienced rainfall changes. The six largest cities—Washington, Houston, New Orleans, Chicago, Cleveland, and St. Louis—all altered their summer precipitation in a rather marked fashion: Precipitation increases of 10 to 30 percent in and downwind of their urban locales, plus associated increases in thunderstorm and hailstorm activity were documented.

²⁶ National Research Council, Committee on Atmospheric Sciences, "Weather and Climate Modification: Problems and Progress," p. 50.

²⁷ Lansford, Henry, "We're Changing the Weather by Accident," *Science Digest*, vol. 74, Dec. 1973, p. 21.

²⁸ Changnon, S. A., Jr., "The La Porte Weather Anomaly—Fact or Fiction?" *Bulletin of the American Meteorological Society*, vol. 49, January 1968, pp. 4-11.

Tulsa and Indianapolis, cities of lower population and lesser physiographic irregularities than the others studied, did not reveal any precipitation anomalies.²⁹

The key questions that could not be answered conclusively at the completion of these climatic studies were (1) whether the anomalies found were real (or adequately measured); (2) if real, what was causing the anomalies; and (3) whether and how extensive the anomalies were around other cities. To this end, a major atmospheric program dealing with inadvertent weather modification was initiated by a group of scientists in 1971. The Metropolitan Meteorological Experiment (METROMEX) was designed by four research groups who received support from Federal agencies and one State (Illinois). St. Louis was chosen as the site of extensive field investigations in this first major field program aimed at studying the reality and causes of urban rainfall anomalies suggested in the climatological surveys conducted previously.³⁰

Although data analysis and report preparation continue (summer 1975 was the fifth and final year for field work), METROMEX data thus far portray statistically significant increases in summer rainfall, heavy (more than 2.5 cm) rainstorms, thunderstorms and hail in and just east (downtown) of St. Louis. Examination of the rainfall yield of individual showers, the spatial distribution of rain developments, and areal distribution of afternoon rain clearly point to the urban-industrial complex as the site for the favored initiation of the rain process under certain conditions.³¹

Writes climatologist Stanley Changnon:

The greater frequency of rain initiations over the urban and industrial areas appears to be tied to three urban-related factors including thermodynamic effects leading to more clouds and greater in-cloud instability, mechanical and thermodynamic effects that produce confluence zones where clouds initiate, and enhancement of the [raindrop] coalescence process due to giant nuclei. Case studies reveal that once additional [rainstorm] cells are produced, nature, coupled with the increased likelihood for merger with more storms per unit area, takes over and produces heavier rainfalls. Hence the city is a focal point for both rain initiation and rain enhancement under conditions when rain is likely.³²

Recapitulating, METROMEX researchers have found that rain, thunderstorms and hail can actually maximize within cities and nearby areas, particularly in those downwind. Such locations may have more storms, and they are more intense, last longer and produce more rain and hail than storms in surrounding regions. Apparently, air heated and polluted by a city can move up through the atmosphere high enough to affect clouds. This urban-modified air clearly adds to the strength of convective storms and increases the severity of precipitation. Urban climatic alterations are summarized in table 1.

²⁹ Huff, F. A. and S. A. Changnon, Jr., "Precipitation Modification by Major Urban Areas," *Bulletin of the American Meteorological Society*, vol. 54, December 1973, pp. 1220-1232.

³⁰ Changnon, S. A., F. A. Huff, and R. G. Semonin, "Metromex: An Investigation of Inadvertent Weather Modification," *Bulletin of the American Meteorological Society*, vol. 52, October 1971, pp. 958-967.

³¹ "METROMEX Update," *Bulletin of the American Meteorological Society*, vol. 57, March 1976, pp. 304-308.

³² Changnon, S. A., R. G. Semonin and F. A. Huff, "A Hypothesis for Urban Rainfall Anomalies," *Journal of Applied Meteorology*, vol. 15, June 1976, pp. 544-560.

TABLE 1.—*Some urban climatic alterations*¹

<i>Element</i>	<i>Comparison with rural environs</i>
Radiation :	
Global	10 to 20 percent less.
Ultraviolet :	
Low sun	30 to 50 percent less.
High sun	5 to 10 percent less.
Temperature :	
Annual mean	1 to 2° C higher.
Maximum difference	3 to 10° C higher.
Winter minima	1 to 3° C higher.
Cloudiness :	
General cloud cover	5 to 10 percent more.
Fog :	
Winter	100 percent more.
Summer	20 to 30 percent more.
Precipitation :	
Totals :	
Summer	10 percent more.
Winter	5 percent more.
Relative humidity : Annual mean	4 to 6 percent less.
Evapotranspiration : Total amount	30 to 60 percent less.
Dew : Amounts	50 to 80 percent less.
Wind speed : < 3 m sec ⁻¹	40 percent less.
Speeds :	
3 — 6 m sec	20 percent less.
> 6 m sec	10 percent less.
Thunderstorms : Number of days	5 to 10 percent more.

¹ After Helmut Landsberg, University of Maryland.

CARBON DIOXIDE AND WATER VAPOR

The constituent gases of the atmosphere that are important variables affecting the distribution of temperature within the atmosphere are carbon dioxide and water vapor. Capable of absorbing important quantities of infrared radiation, they both have a role in modifying the vertical distribution of temperature in the atmosphere by controlling the flux of infrared radiation. The absorption of incoming solar radiation by these gases is so small that their concentration has no appreciable effect on the amount of incoming solar radiation reaching the Earth's surface. Carbon dioxide and water vapor are, however, opaque to major portions of the long-wave radiation emitted by the Earth's surface. The greater the content of these gases the greater the opacity of the atmosphere to infrared radiation and the higher its temperature must be to radiate away the necessary amount of energy to maintain a radiation balance. It is this absorption of long-wave radiation emitted by the Earth, with the subsequent reradiation of additional infrared radiation to the ground and consequent elevation of air temperatures near the surface that is known as the "greenhouse effect."

Increases in atmospheric carbon dioxide concentration: what the record indicates

Man adds carbon dioxide to the atmosphere through the combustion of fossil fuels, and this addition is superimposed on the natural exchanges between the atmosphere, the biosphere, and the world ocean. Since the use of energy has increased exponentially since the beginning

of industrialization around 1860, it is not surprising that the best estimate of carbon dioxide production, which results from fossil fuel combustion and cement manufacture, shows the same exponential trend (see fig. 7).

The concentration of carbon dioxide in the atmosphere has increased steadily from a preindustrial value of about 295 parts per million in 1860 to a current value of 330 parts per million (+ 12 percent). Since the beginning of accurate and regular measurements in 1958, observed atmospheric carbon dioxide concentrations have increased some 5 percent from 315 parts per million to the current yearly average value of 330 parts per million as indicated in figure 8.

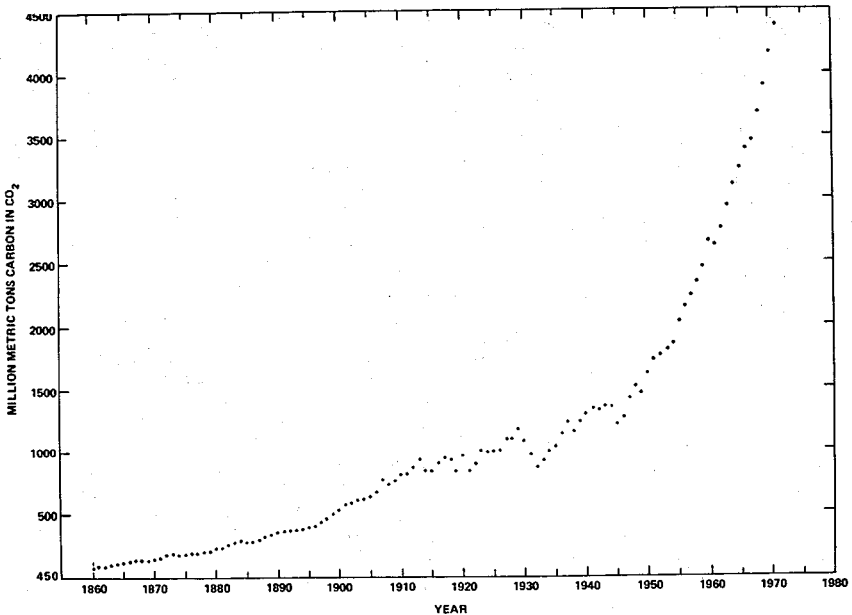


FIGURE 7.—The annual world production of carbon dioxide from fossil fuels (plus a small amount from cement manufacture) is plotted since the beginning of the industrial revolution. Except for brief interruptions during the two world wars and the Great Depression, the release of fossil carbon has increased at a rate of 4.3 percent per year. (Data for 1860–1959 from C. D. Keeling, "Industrial Production of Carbon Dioxide from Fossil Fuels and Limestone," *Tellus*, vol. 25, 1973, p. 174; data for 1960–71 from R. M. Rotty, "Commentary on and Extension of Calculative Procedure for Carbon Dioxide Production," *Tellus*, vol. 25, 1973, p. 508.)

Source: Baes, C. F., et al. "The Global Carbon Dioxide Problem," Oak Ridge National Laboratory, 1976. (ORNL-5194.)

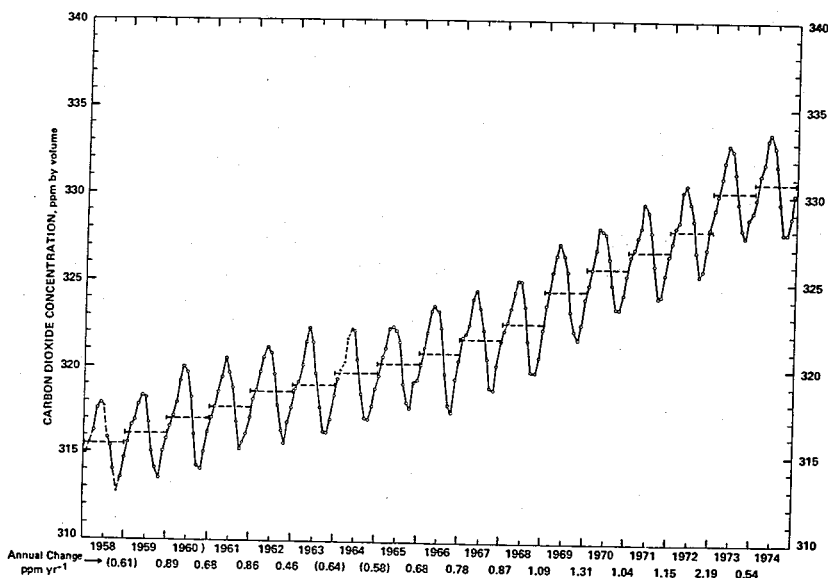


FIGURE 8.—Monthly average values of the concentration of carbon dioxide in the atmosphere at Mauna Loa Observatory, Hawaii, are plotted since the beginning of accurate and regular measurements in 1958. Variations in photosynthesis and other seasonal effects produce the annual cycle. Mean annual concentrations are well above the preindustrial level (290–300 ppm), and the secular increase is quite apparent.

Source: Baes, C. F., et al. "The Global Carbon Dioxide Problem," Oak Ridge National Laboratory, 1978. (ORNL-5194.)

The seasonal variation of the record of carbon dioxide measurements made at Mauna Lao is obvious and regular, showing an October minimum with increases in the later autumn and winter months and a maximum in May. However, of greater importance to possible climatic changes is the continued year-to-year rise. Both the seasonal variation and the annual increase have been confirmed by measurements at other locations around the globe.

Predicting future atmospheric carbon dioxide levels

Projecting the worldwide needs for energy, even with the present problems, indicates a long-term global growth in the consumption of fossil fuels and the associated production of carbon dioxide. Insofar as possible impact on the climate is concerned, it is the amount of carbon dioxide remaining in the atmosphere that is most important. In addition to the atmosphere, the ocean and both land and marine biospheres serve as reservoirs for carbon dioxide. Based on estimates of preindustrial levels of atmospheric carbon dioxide of 290–295 parts per million and the 1958 to present Mauna Loa data, between 58 and 64 percent of the carbon dioxide produced from burning fossil fuels remains in the atmosphere. Cumulative production of carbon dioxide is plotted in figure 9. The upper set of points indicates the increase in the carbon dioxide fraction of the atmosphere that would have occurred if all car-

bon dioxide produced since 1860 from fossil fuels and cement remained airborne. The lower set of points represents the observed increase based on an assumed value of 290–295 parts per million in 1860. The difference between the two sets of points presumably indicates the amount of carbon dioxide being taken up by the world ocean and possibly the biosphere and placed in long-term storage. Nearly half of the carbon dioxide produced from fossil fuels and cement seems to have found its way into reservoirs other than the atmosphere.

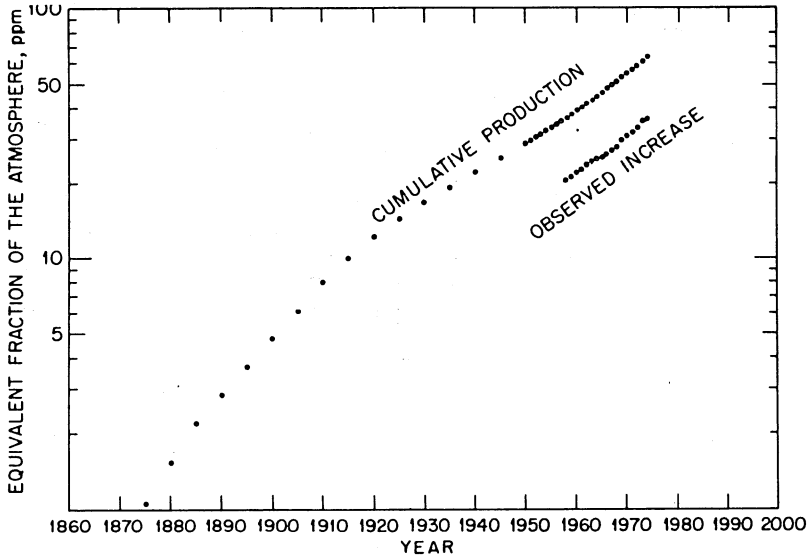


FIGURE 9.—The cumulative production of carbon dioxide since 1860 is compared with the observed increase in the mean annual concentration since that time. The similarity in the rates of increase (about 4 percent per year) produces strong evidence that these two quantities are related. About 50 percent of the fossil carbon flux apparently has been balanced, at least since 1958, by a flow of carbon dioxide to such reservoirs at the world ocean and/or the land biota (assumed 1860 atmospheric concentration equals 295 ppm).

Source: Baes, C. F., et al. "The Global Carbon Dioxide Problem," Oak Ridge National Laboratory, 1976. (ORNL-5194.)

Future levels of atmospheric carbon dioxide will depend primarily on the rate of consumption of fossil fuel and to a lesser extent on land use patterns and practices. With brief interruptions for two world wars and the Great Depression, the production of carbon dioxide from fossil fuels has increased with an annual rate of 4.3 percent.³³ If the use of fossil fuels continues to grow at this present rate, the total carbon dioxide injected into the atmosphere by man since 1860 would reach 300 parts per million by the year 2030, and the total concentration would be equal to 595 parts per million. This assumes, of course, no change in the average uptake by other reservoirs during this time. Those energy scenarios that rely heavily on coal, especially for synthetic oil and gas, yield estimated carbon dioxide concentrations of

³³ 4.3 percent per year provides an excellent fit to the data in figure 7.

600 parts per million about the year 2015 and 1,400 parts per million about 100 years from now. Rotty and Weinberg (1977) discuss a scenario by Niehaus in which nonfossil energy sources dominate soon after 2000. Even in this case the annual emission of carbon dioxide from fossil fuel peaks at about twice the present level in the year 2000 and tapers off thereafter; the atmospheric concentration nevertheless reaches 475 parts per million by 2050.^{34, 35, 36, 37, 38}

Sources and sinks for carbon dioxide

These extrapolations are based on certain assumptions, a critical one being that the ocean and the biosphere will continue to absorb a large fraction of the carbon dioxide in the atmosphere. Some oceanographers see increasing evidence that the upper mixed layer of the ocean, where most of the carbon dioxide is stored, is rapidly becoming saturated, and if this were true, then it tends to reenforce the attainment of relatively high atmospheric carbon dioxide concentrations in the next century. However, this prediction is far from certain, because carbon dioxide absorption in the ocean could turn out to be greater than expected because of mixing between ocean layers or other factors.³⁹ The problem is further complicated by a series of current appraisals that suggest that the terrestrial biomass appears to be a net source of carbon dioxide for the atmosphere. George M. Woodwell of the Marine Biological Laboratory at Woods Hole, Mass., explains:

Over the past seven years several reviews of the world carbon budget have confirmed that there is an annual increase in the carbon dioxide content of [the atmosphere] that is worldwide and is almost certainly man-caused. The source of the carbon dioxide that is accumulating in the atmosphere has been commonly assumed to be the combustion of fossil fuels. Because the amount of carbon dioxide accumulating in the atmosphere is * * * [about] half the total released from fossil fuels, other sinks for carbon dioxide have been sought. The major sink is the ocean, but mixing rates appear to be too low for the oceans to accommodate all the carbon dioxide that is thought to be released in excess of that accumulating in the atmosphere. The question of whether the terrestrial biota could be another sink was raised in 1970 [at SCEP], and the assumption was made that the biota might be a sink, especially in view of the stimulation of photosynthesis under greenhouse conditions by enhanced concentrations of carbon dioxide. More recently, the assumption that increased carbon dioxide in air stimulates photosynthesis worldwide has been questioned. So has the assumption that the biota is a net global sink for carbon dioxide. A series of current appraisals suggests that, quite contrary to the previous estimates, the biota is probably an additional source of carbon dioxide * * * as large as or larger than the fossil fuel source.⁴⁰

Thus, the great puzzle is the basic stability of the global carbon budget. Without better information on the behavior of the terrestrial biosphere, it is difficult to say whether the biosphere is a sink or a net source of carbon dioxide. If the biosphere is supplying more carbon

³⁴ Baes, C. F., Jr., et al. "The Global Carbon Dioxide Problem," Oak Ridge, Tenn., Oak Ridge National Laboratory, 1976. 78 pp. (ORNL-5194.)

³⁵ Lepkowski, Wil. "Carbon Dioxide: A Problem of Producing Usable Data." *Chemical and Engineering News*, vol. 55, Oct. 17, 1977: pp. 26-30.

³⁶ Rotty, Ralph M. "Energy and the Climate." Institute for Energy Analysis, Oak Ridge, Oak Ridge Associated Universities, 1976. 28 pp. (ORAU/IEA (M) 75-3.)

³⁷ Rotty, R. M. and A. M. Weinberg. "How Long is Coal's Future," *Climatic Change*, vol. 1, No. 1, March 1977: pp. 45-57.

³⁸ Rotty, Ralph M. "The Atmospheric Carbon Dioxide Consequences of Heavy Dependence on Coal." Institute for Energy Analysis, Oak Ridge Associated Universities, occasional paper. 32 pp. Nov. 14, 1977.

³⁹ Anthes, Richard A., Hans A. Panofsky, John J. Cahiri and Albert Rango, "The Atmosphere," Columbus, Charles E. Merrill Publishing Co., 1975, p. 204.

⁴⁰ Woodwell, G. M., et al., "The Biota and the World Carbon Budget." *Science*, vol. 199, Jan. 13, 1978, pp. 141-146.