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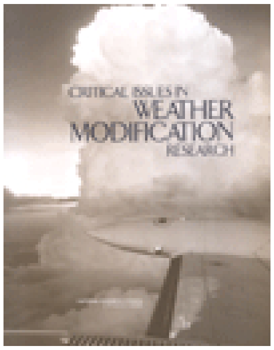
Critical Issues in Weather Modification Research



Committee on the Status and Future Directions in U.S
Weather Modification Research and Operations,
National Research Council

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CRITICAL ISSUES IN WEATHER MODIFICATION RESEARCH

Committee on the Status of and Future Directions in
U.S. Weather Modification Research and Operations

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
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Cover: Photograph taken by Dr. William L. Woodley at 7:39 pm CDT on August 11, 2001, from a Texas seeder aircraft flying at 20,000 ft. The cloud shown reaching cumulonimbus stature had been seeded near its top 10 minutes earlier with ejectable silver iodide pyrotechnics.

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Preface

The growing evidence that human activities can affect the weather on scales ranging from local to global has added a new and important dimension to the place of weather modification in the field of atmospheric sciences. There is a need, more urgent than ever, to understand the fundamental processes related to intentional and unintentional changes in the atmosphere. The question of how well current technology, practice, and theory are equipped to meet these broader goals of weather modification is central to this report. The challenge to find the right balance between assured knowledge and the need for action is one which must guide the future actions of both scientists and administrators concerned with weather modification.

Difficulties demonstrating repeatability of weather modification experiments, providing convincing scientific evidence of success, and overcoming serious social and legal problems led to the moderation of the early predictions of success in weather modification by the late 1970s. The need to understand the fundamental physical and chemical processes underlying weather modification became obvious, thus a dedicated research effort was repeatedly recommended by successive national panels. Failure to devote significant public and private resources to basic research polarized both the support agencies and scientific community, generating serious feelings of ambivalence within these communities toward weather modification.

Despite significant advances in computational capabilities to deal with complex processes in the atmosphere and remarkable advances in observing technology, little of this collective power has been applied in any coherent way to weather modification. The potential for progress in weather modification as seen by this Committee is dependent upon an improved fundamental understanding of crucial cloud, precipitation, and larger-scale atmospheric processes. The Committee believes that such progress is now within reach should the above advances be applied in a sustained manner to answer fundamental outstanding questions. While the Committee acknowledges the prospect of achieving significant advances in the ability of humans to exercise a degree of control over the weather, we caution that such progress is not possible without a concerted and sustained effort at understanding basic processes in the atmosphere. Furthermore, such results are as likely to lead to viable weather modification methodologies as they are to indicate that intentional modification of a weather system is neither currently possible nor desirable.

A significant part of the advances projected from applying the current intellectual and technological tools to solving critical uncertainties in weather modification will produce results well beyond the initial objective and will lead to applications in totally unexpected areas. For example, the ability to make useful precipitation forecasts, particularly from convective storms, may be a valuable by-product of weather modification research. The Committee is also acutely conscious of the fact that, particularly in modifying severe weather, researchers may be required to have, before attempting treatment, a reliable and proven ability to predict what would have taken place had the system not been modified. As a chaotic system, the atmosphere is inherently predictable only for a limited time, with the time limit shorter for smaller spatial scales. Thus, predictions must be couched in probabilistic terms that may not satisfy the user community that a reliable prediction has been made.

This report is the latest in a series of assessments of weather modification carried out by the National Academies, which produced reports in 1964, 1966, and 1973, aimed at guiding weather modification research and policy development. The last National Academies report is nearly three decades old and, despite more recent assessments by other bodies such as the American Meteorological Society and the World Meteorological Organization, a need was seen for an evaluation of weather modification research and operations in the United States.

In November 2000, the National Academies' Board on Atmospheric Sciences and Climate (BASC) organized a program development workshop to assess whether it would be useful to take a fresh look at the scientific underpinnings of weather modification. A year later, a study committee was convened, and four committee meetings were held over eight months. The Committee received input from individuals in federal and state agencies, scientists who have or are conducting relevant research, and professionals active in operational weather programs. The charge to the Committee explicitly excluded consideration of the complex social and legal issues associated with weather modification. This part of the question is of such importance in any weather modification effort that the Committee did go so far as to note, but not elaborate upon, the most critical questions in this area. Also in accordance with its charge, the Committee did not address inadvertent global-scale modification of climate and weather (e.g., global warming). However, the potential local and regional impacts of both intentional and inadvertent weather modification are considered.

The report is addressed primarily to Administration officials and funding agencies who determine the direction of atmospheric research through budget decisions. The Committee recognizes, however, that weather modification has a wide audience. The Preface and the Executive Summary are directed at this wider audience, while a greater level of technical detail is contained within the body of the report.

Michael Garstang, Chair
Committee on the Status of and
Future Directions in U.S. Weather
Modification Research and Operations

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Richard Anthes, University Corporation for Atmospheric Research
Rafael Bras, Massachusetts Institute of Technology
Stanley A. Changnon, Illinois State Water Survey
William Cotton, Colorado State University
John Hallett, Desert Research Institute
Daniel Rosenfeld, Hebrew University
Joanne Simpson, NASA Goddard Space Flight Center
Gabor Vali, University of Wyoming
Francis Zwiers, University of Victoria

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John A. Dutton, The Pennsylvania State University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

The weather on planet Earth is a vital and sometimes fatal force in human affairs. Efforts to control or reduce the harmful impacts of weather go back far in time. In recent decades our ability to observe and predict various types of meteorological systems has increased tremendously. Yet during this same period there has been a progressive decline in weather modification research. Extravagant claims, unrealistic expectations, and failure to provide scientifically demonstrable success are among the factors responsible for this decline. Significantly, every assessment of weather modification dating from the first National Academies' report in 1964 has found that scientific proof of the effectiveness of cloud seeding was lacking (with a few notable exceptions, such as the dispersion of cold fog). Each assessment also has called for a dedicated research effort directed at removing or reducing basic scientific uncertainties before proceeding with the application of weather modification methods. Yet, this type of intensive, committed effort has not been carried out.

In this, the latest National Academies' assessment of weather modification, the Committee was charged to provide an updated assessment of the ability of current and proposed weather modification capabilities to provide beneficial impacts on water resource management and weather hazard mitigation. It was asked to examine new technologies, such as ground-based, in situ, and satellite detection systems, and fast reacting seeding materials and dispensing methods. The Committee also was asked to review advances in numerical modeling on the cloud- and meso-scale and consider how improvements in computer capabilities might be applied to weather modification. This study was not designed to address policy implications of weather modification; rather it focused on the research and operational issues. Specifically, the Committee was asked to:

- review the current state of the science of weather modification and the role of weather prediction as it applies to weather modification, paying particular attention to the technological and methodological developments of the last decade;
- identify the critical uncertainties limiting advances in weather modification science and operation;

- identify future directions in weather modification research and operations for improving the management of water resources and the reduction in severe weather hazards; and
- suggest actions to identify the potential impacts of localized weather modification on large-scale weather and climate patterns.

ISSUES AND TRENDS IN WEATHER MODIFICATION

Motivation

Increasing demands for water make the potential for enhancing the sources, storage, and recycling of freshwater a legitimate area of study. Destruction and loss of life due to severe weather, which is increasing with population growth and changing demographics, require that we examine ways to reduce these impacts. In addition, there is ample evidence that human activities, such as the emission of industrial air pollution, can alter atmospheric processes on scales ranging from local precipitation patterns to global climate. These inadvertent impacts on weather and climate require a concerted research effort, yet the scientific community has largely failed to take advantage of the fact that many of the scientific underpinnings of intentional and unintentional weather modification are the same.

Current Operational and Research Efforts

Operational weather modification programs, which primarily involve cloud-seeding activities aimed at enhancing precipitation or mitigating hail fall, exist in more than 24 countries, and there were at least 66 operational programs being conducted in 10 states across the United States in 2001. No federal funding currently is supporting any of these operational activities in the United States. Despite the large number of operational activities, less than a handful of weather modification research programs are being conducted worldwide. After reaching a peak of $20 million per year in the late 1970s, support for weather modification research in the United States has dropped to less than $500,000 per year.

The Paradox

Clearly, there is a paradox in these divergent trends: The federal government is not willing to fund research to understand the efficacy of weather modification technologies, but others are willing to spend funds to apply these unproven techniques. Central to this paradox is the failure of past cloud-seeding experiments to provide an adequate verification of attempts at modifying the weather. A catch-22 ensues in which the inability to provide acceptable proof damages the credibility of the entire field, resulting in diminished scientific effort to address problems whose solutions would almost certainly lead to better evaluations.

Limitations and Problems

The dilemma in weather modification thus remains. We know that human activities can affect the weather, and we know that seeding will cause some changes to a cloud. However, we still are unable to translate these induced changes into verifiable changes in rainfall, hail fall, and snowfall on the ground, or to employ methods that produce credible, repeatable changes in precipitation. Among the factors that have contributed to an almost uniform failure to verify seeding effects are such uncertainties as the natural variability of precipitation, the inability to measure these variables with the required accuracy or resolution, the detection of a small induced effect under these conditions, and the need to randomize and replicate experiments.

CONCLUSIONS

The Committee concludes that there still is no convincing scientific proof of the efficacy of intentional weather modification efforts. In some instances there are strong indications of induced changes, but this evidence has not been subjected to tests of significance and reproducibility. This does not challenge the scientific basis of weather modification concepts. Rather it is the absence of adequate understanding of critical atmospheric processes that, in turn, lead to a failure in producing predictable, detectable, and verifiable results. Questions such as the transferability of seeding techniques or whether seeding in one location can reduce precipitation in other areas can only be addressed through sustained research of the underlying science combined with carefully crafted hypotheses and physical and statistical experiments.

Despite the lack of scientific proof, the Committee concludes that scientific understanding has progressed on many fronts since the last National Academies' report and that there have been many promising developments and advances. For instance, there have been substantial improvements in the ice-nucleating capabilities of new seeding materials. Recent experiments using hygroscopic seeding particles in water and ice (mixed-phase) clouds have shown encouraging results, with precipitation increases attributed to increasing the lifetime of the rain-producing systems. There are strong suggestions of positive seeding effects in winter orographic glaciogenic systems (i.e., cloud systems occurring over mountainous terrain). Satellite imagery has underlined the role of high concentrations of aerosols in influencing clouds, rain, and lightning, thus drawing the issues of intentional and inadvertent weather modification closer together. This and other recent work has highlighted critical questions about the microphysical processes leading to precipitation, the transport and dispersion of seeding material in the cloud volume, the effects of seeding on the dynamical growth of clouds, and the logistics of translating storm-scale effects into an area-wide precipitation effect. By isolating these critical questions, which currently hamper progress in weather modification, future research efforts can be focused and optimized.

Additional advances in observational, computational, and statistical technologies have been made over the past two to three decades that could be applied to weather modification. These include, respectively, the capabilities to (1) detect and quantify relevant variables on temporal and spatial scales not previously possible; (2) acquire, store, and process vast quantities of data; and (3) account for sources of uncertainty and incorporate complex spatial and temporal relationships. Computer power has enabled the development of models that range in scale from a single cloud to the global atmosphere. Numerical modeling simulations—validated by observations whenever possible—are useful for testing intentional weather modification and corresponding larger-scale effects. Few of these tools, however, have been applied in any collective and concerted fashion to resolve critical uncertainties in weather modification. These numerous methodological advances thus have not resulted in greater scientific understanding of the principles underlying weather modification. This has not been due to flawed science but to the lack of support for this particular field of the science over the past few decades. As a result there still is no conclusive scientific proof of the efficacy of intentional weather modification, although the probabilities for seeding-induced alterations are high in some instances. Despite this lack of scientific proof, operational weather modification programs to increase rain and snowfall and to suppress hail formation continue worldwide based on cost versus probabilistic benefit analyses.

RECOMMENDATIONS

Recommendation: Because weather modification could potentially contribute to alleviating water resource stresses and severe weather hazards, because weather modification is being attempted regardless of scientific proof supporting or refuting its efficacy, because inadvertent atmospheric changes are a reality, and because an entire suite of new tools and techniques now exist that could be applied to this issue, the Committee recommends that there be a renewed commitment to advancing our knowledge of fundamental atmospheric processes that are central to the issues of intentional and inadvertent weather modification. The lessons learned from such research are likely to have implications well beyond issues of weather modification. Sustainable use of atmospheric water resources and mitigation of the risks posed by hazardous weather are important goals that deserve to be addressed through a sustained research effort.

Recommendation: The Committee recommends that a coordinated national program be developed to conduct a sustained research effort in the areas of cloud and precipitation microphysics, cloud dynamics, cloud modeling, and cloud seeding; it should be implemented using a balanced approach of modeling, laboratory studies, and field measurements designed to reduce the key uncertainties listed in Box ES.1. This program should not focus on near-term operational applications of weather modification; rather it should address fundamental research questions from these areas that currently impede progress and understanding of intentional and inadvertent weather modification. Because a comprehensive set of specific research questions cannot possibly be listed here, they should be defined by individual proposals funded by a national program. Nevertheless, examples of such questions may include the following:

- What is the background aerosol concentration in various places, at different times of the year, and during different meteorological conditions? To what extent would weather modification operations be dependent on these background concentrations?

- What is the variability of cloud and cell properties (including structure, intensity, evolution, and lifetime) within larger clusters, and how do clouds and cells interact with larger-scale systems? What are the effects of localized seeding on the larger systems in which the seeded clouds are embedded?
- How accurate are radar reflectivity measurements in measuring the differences between accumulated rainfall in seeded and unseeded clouds? How does seeding affect the drop-size distribution that determines the relationship between the measured radar parameter and actual rainfall at the surface?

BOX ES.1

Summary of Key Uncertainties

The statements in boldface type are considered to have the highest priority.

Cloud/precipitation microphysics issues

- **Background concentration, sizes, and chemical composition of aerosols that participate in cloud processes**
- Nucleation processes as they relate to chemical composition, sizes, and concentrations of hygroscopic aerosol particles
- Ice nucleation (primary and secondary)
- Evolution of the droplet spectra in clouds and processes that contribute to spectra broadening and the onset of coalescence
- Relative importance of drizzle in precipitation processes

Cloud dynamics issues

- **Cloud-to-cloud and mesoscale interactions as they relate to updraft and downdraft structures and cloud evolution and lifetimes**
- Cloud and sub-cloud dynamical interactions as they relate to precipitation amounts and the size spectrum of hydrometeors
- Microphysical, thermodynamical, and dynamical interactions within clouds

Cloud modeling issues

- **Combination of the best cloud models with advanced observing systems in carefully designed field tests and experiments**
- Extension of existing and development of new cloud-resolving models explicitly applied to weather modification
- Application of short-term predictive models including precipitation forecasts and data assimilation and adjoint methodology in treated and untreated situations
- Evaluation of predictive models for severe weather events and establishment of current predictive capabilities including probabilistic forecasts
- Advancement of the capabilities in cloud models to simulate dispersion trajectories of seeding material
- Use of cloud models to examine effects of cloud seeding outside of seeded areas
- Combination of cloud models with statistical analysis to establish seeding effects

Seeding-related issues

- **Targeting of seeding agents, diffusion and transport of seeding material, and spread of seeding effects throughout the cloud volume**
- **Measurement capabilities and limitations of cell-tracking software, radar, and technologies to observe seeding effects**
- Analysis of recent observations with new instruments of high concentrations of ice crystals
- Interactions between different hydrometeors in clouds and how to best model them
- Modeling and prediction of treated and untreated conditions for simulation
- Mechanisms of transferring the storm-scale effect into an area-wide precipitation effect and tracking possible downwind changes at the single cell, cloud cluster, and floating target scales

The tasks involved in weather modification research fall within the mission responsibilities of several government departments and agencies, and careful coordination of these tasks will be required.

Recommendation: The Committee recommends that this coordinated research program include:

- **Capitalizing on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems** (e.g., Doppler lidars and airborne radars, microwave radiometers, millimeter-wave and polarimetric cloud radars, global positioning system (GPS) and cell-tracking software, the Cloud Particle Imager, the Gerber Particle Volume Monitor, the Cloud Droplet Spectrometer). Initial field studies should concentrate on areas that are amenable to accurate numerical simulation and multiparameter, three-dimensional observations that allow the testing of clearly formulated physical hypotheses. Some especially promising possibilities where substantial further progress may occur (not listed in any priority) include

    ➢ *Hygroscopic seeding to enhance rainfall.* The small-scale experiments and larger-scale coordinated field efforts proposed by the Mazatlan workshop on hygroscopic seeding (WMO, 2000) could form a starting point for such efforts. A randomized seeding program with concurrent physical measurements (conducted over a period as short as three years) could help scientists to either confirm or discard the statistical results of recent experiments.

    ➢ *Orographic cloud seeding to enhance precipitation.* Such a program could build on existing operational activities in the mountainous western United States. A randomized program that includes strong modeling and observational components, employing advanced computational and observational tools, could substantially enhance our understanding of seeding effects and winter orographic precipitation.

    - ➢ *Studies of specific seeding effects.* This may include studies such as those of the initial droplet broadening and subsequent formation of drizzle and rain associated with hygroscopic seeding, or of the role of large (>1 μm) particles (e.g., sea spray) in reducing droplet concentrations in polluted regions where precipitation is suppressed due to excess concentrations of small cloud condensation nuclei (CCN).

- **Improving cloud model treatment of cloud and precipitation physics.** Special focus is needed on modeling CCN, ice nuclei processes, and the growth, collision, breakup, and coalescence of water drops and ice particles. Such studies must be based on cloud physics laboratory measurements, tested and tuned in model studies, and validated by in situ and ground observations.

- **Improving and using current computational and data assimilation capabilities.** Advances are needed to allow rapid processing of large quantities of data from new observations and better simulation of moist cloud and precipitation processes. These models could subsequently be used as planning and diagnostic tools in future weather modification studies, and to develop techniques to assist in the evaluation of seeding effects.

- **Capitalizing on existing field facilities and developing partnerships among research groups and select operational programs**. Research in weather modification should take full advantage of opportunities offered by other field research programs and by operational weather modification activities. Modest additional research efforts directed at the types of research questions mentioned above can be added with minimal interference to existing programs. A particularly promising opportunity for such a partnership is the Department of Energy Atmospheric Radiation Measurement program/Cloud and Radiation Test bed (DOE ARM/CART) site in the southern Great Plains (Oklahoma/Kansas) augmented by the National Aeronautics and Space Administration (NASA) Global Precipitation Mission. This site provides a concentration of the most advanced observing systems and an infrastructural base for sustained basic research. The National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory (NOAA/ETL) also could serve as important focal points for weather modification research.

In pursuing research related to weather modification explicit, financial and collegial support should be given to young aspiring scientists to enable them to contribute to our fundamental store of knowledge about methods to enhance atmospheric resources and reduce the impacts of hazardous weather. It must be acknowledged that issues related to weather modification go well beyond the limits of physical science. Such issues involve society as a whole, and scientific weather modification research should be accompanied by parallel social, political, economic, environmental, and legal studies.

The Committee emphasizes that weather modification should be viewed as a fundamental and legitimate element of atmospheric and environmental science. Owing to the growing demand for fresh water, the increasing levels of damage and loss of life resulting from severe weather, the undertaking of operational activities without the guidance of a careful scientific foundation, and the reality of inadvertent atmospheric changes, the scientific community now has the opportunity, challenge, and responsibility to assess the potential efficacy and value of intentional weather modification technologies.

1

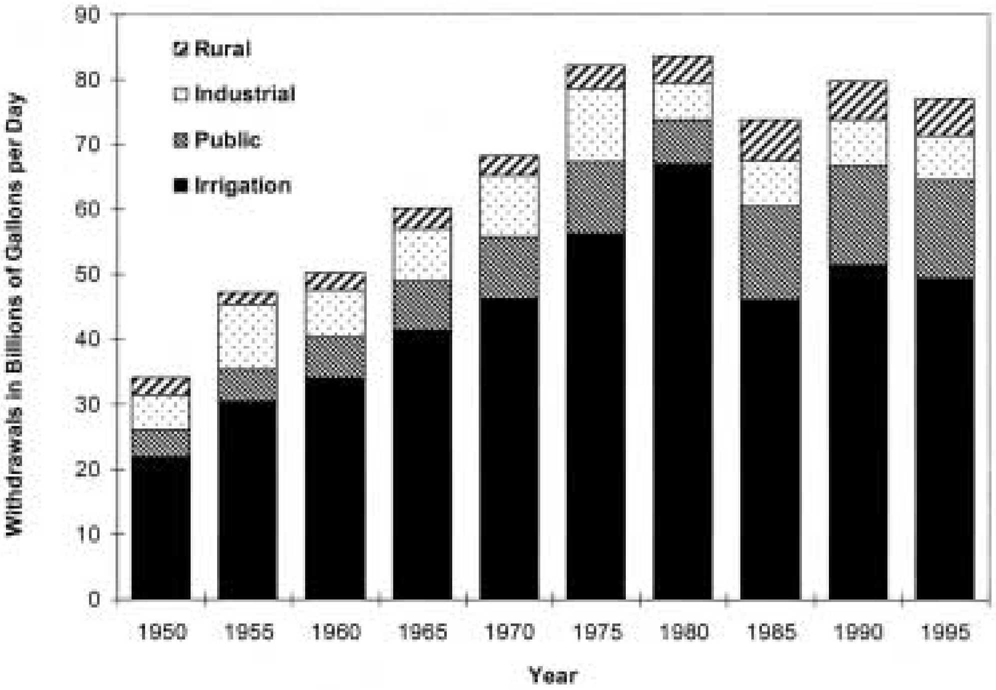
Introduction

MOTIVATION

Societal interest and investment in weather modification have been driven historically by the needs for increased water and for reduced damage from hazardous weather. In many places around the world, freshwater resources are becoming increasingly strained. Recent analyses find that nearly two billion people are currently considered subject to severe water shortage, and this number is projected to increase to over three billion during the next 25 years (Plate 1). Factors such as population growth, economic development, and global climate change are contributing to this expanding stress and leading to ever-increasing water use for domestic, industrial, and agricultural purposes. Agriculture alone is responsible for over 70 percent of global freshwater use, primarily for irrigation (Montaigne, 2002).

During three-quarters of the last century, increases in withdrawals from ground water reserves in the United States exceeded population growth. Economic, environmental, and governmental factors recently have slowed this imbalance, and there are encouraging signs that after a sustained 30-year growth in ground water withdrawals nationwide, these trends now are stabilizing (Figure 1.1). However, a continuing depletion of groundwater reserves is still occurring in some large aquifers (Figure 1.2), and water resource needs are increasing rapidly in many other parts of the world. History is replete with examples of local and regional conflicts over water. Meeting the pressing need for clean, sustainable, and adequate water supplies will require comprehensive resource management strategies that include water conservation and efficiency measures, but there could also be tremendous societal benefits from taking actions to increase water supplies in select areas.

Hazardous weather such as hail, strong thunderstorm and tornadic winds, hurricanes, lightning, and floods pose a significant threat to life and property. Table 1.1 shows the costs of severe weather in the United States in terms of fatalities, injuries, and property damage. In developing countries with less protective infrastructure, the toll of severe weather sometimes can be especially devastating; for example, in 1998 Hurricane Mitch spawned mudslides in Honduras that killed over 10,000 people. Clearly it is



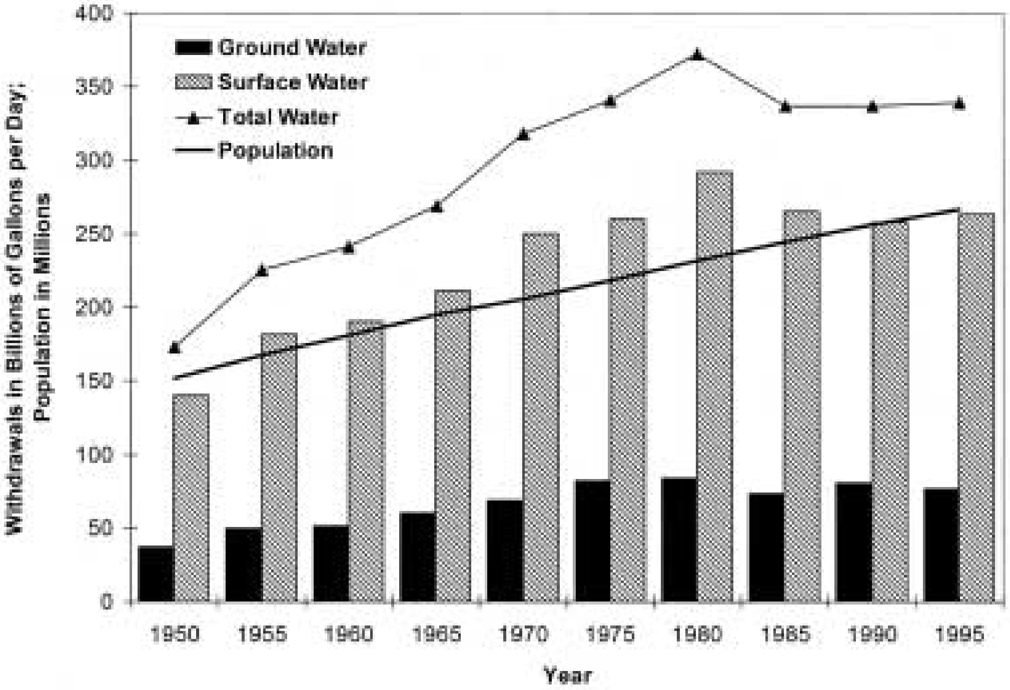


FIGURE 1.1 Top figure: Ground-water usage in the United States, by sector. Bottom figure: Trends in water withdrawals in the United States. SOURCE: U.S. Geological Survey (2002).

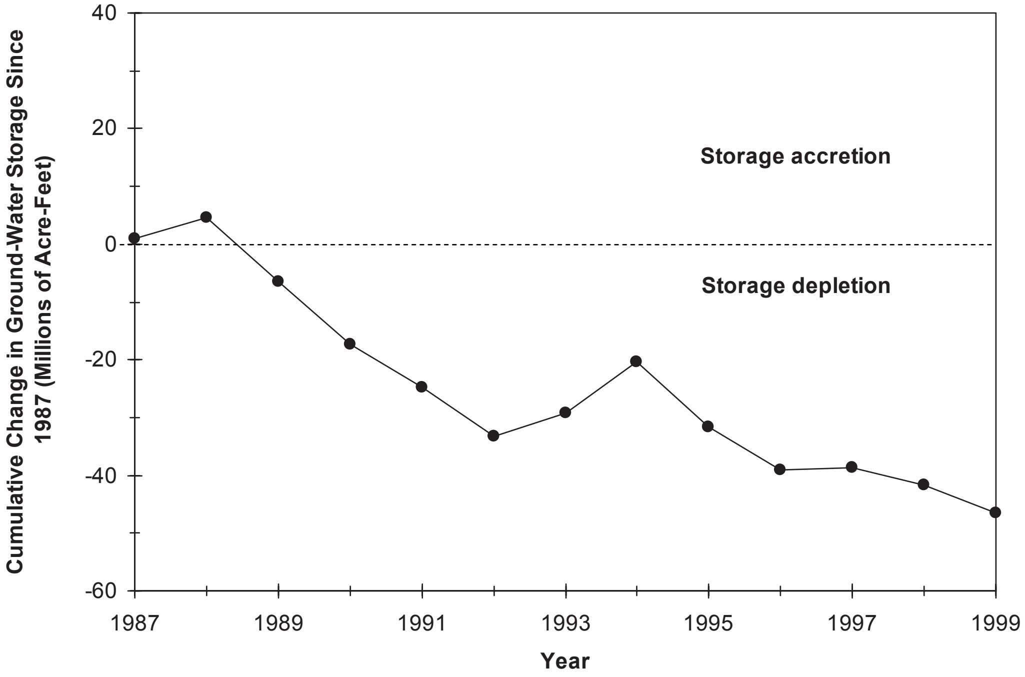


FIGURE 1.2 Cumulative changes in ground-water storage since 1987, High Plains aquifer. SOURCE: Solley et al. (1998).

TABLE 1.1 Summary of Natural Hazard Statistics for 2001 in the United States

Weather Event	Fatalities	Injuries	Property Damage (Millions of $)	Crop Damage (Millions of $)
Lightning	44	371	43.6	2.0
Tornado	40	743	630.1	7.4
Severe thunderstorm	17	341	317.8	61.0
Hail	0	32	2,368.3	270.4
Floods	48	277	1,220.3	43.0
Coastal storm	53	96	17.7	0
Hurricane	24	7	5,187.8	2.7
Winter storm	18	173	103.6	0.1
Fog	7	67	1.3	0
High wind	14	98	63.8	2.2

SOURCE: National Oceanic and Atmospheric Administration/National Weather Service. Adapted from http://www.nws.noaa.gov/om/severe_weather/sum01.pdf.

important to mitigate society's vulnerability to hazardous weather through actions such as improving construction standards for buildings, relocating residents from hazard-prone areas, and providing more accurate warnings. However, there might be substantial additional societal benefits to reducing the intensity or occurrence of hazardous weather events through direct interventions in atmospheric processes.

Whether or not methods for weather modification ultimately prove effective in providing significant benefits, these expanding societal stresses and threats will continue to make periodic reassessment of the science and technology underlying weather modification a national need. Searching for ways to enhance precipitation and mitigate hazardous weather is one of the most important challenges that could be tackled by science. Even relatively minor changes in weather could be of profound benefit. This possibility was recognized immediately upon reports of the first cloud-seeding experiments: In congressional hearings in 1951, Dr. Vannevar Bush, president of the Carnegie Institute, testified, "I have become convinced that it is possible under certain circumstances to make rain. As it stands today, we are on the threshold of an exceedingly important matter, for man has begun for the first time to affect the weather in which he lives, and no man can tell where such a move finally will end." (U.S. H.R., 1953).

BOX 1.1
Socio-economic Implications of Weather Modification

The Committee's charge calls for this study to focus on research and operational issues and instructs it not to address the policy implications of weather modification. Although the Committee has not investigated policy and related socio-economic issues (e.g., liability concerns, cost-benefit analyses, societal attitudes), it recognizes that the motivational factors for applied research and operational activities in weather modification are intimately linked to these issues. For instance, weather modification is aimed primarily at controlling the spatial and temporal distribution of precipitation, which can potentially raise contentious liability issues (i.e., the metaphoric "robbing Peter to pay Paul"). Furthermore, societal attitudes toward "tampering with nature" are often linked to need; people living in drought-prone or water-stressed regions will do what they deem necessary out of desperation. The Committee believes that sound, validated scientific research results can ultimately provide the critical answers needed to address these political and socio-economic issues appropriately.

In addition, the Committee recognizes that even if significant, reliable precipitation enhancement techniques were to eventually become feasible (e.g., if it becomes possible to increase rainfall by up to 20 percent everywhere that is needed), this alone is unlikely to provide a long-term solution for water resources in areas of the world that are most water stressed. There are a variety of proven, cost-effective societal and technological approaches (e.g., water conservation, precision irrigation, improved building codes in coastal areas) that undoubtedly will continue to play an important role in water resource management and hazard mitigation.

This quotation illustrates the initial enthusiasm for cloud seeding. As late as 1978, the Department of Commerce Weather Modification Advisory Board (1978) reported that "a usable technology for significantly enhancing rain and snow and ameliorating some weather damage is scientifically possible and within sight." This conclusion ultimately proved to be too optimistic regarding the time required to realize that possibility, in part because the recommended research program was not pursued (Lambright and Changnon, 1989). The stated goals, however, remain as real today as they were when these statements were first made.

Since that time, weather modification has largely been relegated to the realm of promises unfulfilled. Weather modification does not appear as a line item in the budget of any federal agency—although closely related topics such as cloud physics, water management, and climate change are being pursued—and no work is being done on the complex social and economic implications of attempts to modify weather (see Box 1.1). Yet people in drought-prone areas willingly spend significant resources in support of cloud seeding to increase rain, and commercial operations for increasing mountain snowpack have been supported continuously for many years (Plate 2). But all the while, science is unable to say with assurance which, if any, seeding techniques produce positive effects. In the 55 years following the first cloud-seeding demonstrations, substantial progress has been made in understanding the natural processes that account for our daily weather. Yet scientifically acceptable proof for significant seeding effects has not been achieved, and the scientific challenges have proved to be significantly more formidable and complex than perceived initially.

CLOUD PHYSICS

Most attempts at modifying weather in the modern era have aimed at initiating the onset, or accelerating the rates of, the physical-chemical processes involved in precipitation formation. Significant amounts of precipitation can occur only when low-level atmospheric convergence and upward movement of air parcels provide water vapor for conversion into cloud drops. Thus, a complete understanding of the formation of natural precipitation requires understanding the dynamics of atmospheric motions as well as the physical processes governing formation and growth of cloud and precipitation particles.

The physical processes taking place within a cloud that lead to precipitation are very complex and depend, among other things, on the number and characteristics of aerosol particles in the cloud-forming air. The atmosphere contains a tremendous amount of particulate matter from a wide variety of natural and anthropogenic sources. These include, for example, soot, sea salt, volcanic ash, wind-blown sand and dust, biogenically-derived materials such as pollens and spores, and a variety of sulfur, nitrogen, and carbon compounds (which often result from industrial pollution, biomass burning, and other combustion processes). Soluble and hydrophilic particles absorb water and can eventually act as CCN. Some insoluble particles with wettable surfaces may adsorb water and serve as large cloud drop nuclei or ice nuclei. Some insoluble particles have a crystalline structure that provides an efficient starting place for ice crystals to grow and thus are referred to as ice nuclei (IN); the exact composition of most IN is not well known.

Differences in the initial population of atmospheric aerosols affect the cloud particle and cloud drop populations, which subsequently affect the amount of precipitation reaching the ground. There is considerable uncertainty as to just how the various IN and CCN activate, how concentrations vary of giant CCN or ultra-giant particles (UGP) and their impact on coalescence broadening, how cloud particles interact and evolve by collision and breakup processes, how winds and electric fields in a cloud evolve and affect the growth and interaction of cloud particles, and how individual clouds interact, among other fundamental questions.

There are several different physical pathways (often called mechanisms) through which precipitation may form in natural clouds. Local conditions of updraft speed, temperature, pressure, initial aerosol characteristics, and cloud and precipitation particle concentrations and size distributions govern the rates of progress along these pathways. Several mechanisms may be active simultaneously, each affecting the others. Often one of the mechanisms proceeds faster than the others and becomes dominant. For the purposes of this report, and at the risk of oversimplification, it is useful to group these mechanisms into those that involve the formation of ice particles and those that do not.

The so-called coalescence mechanism—or warm-cloud precipitation mechanism—is an all-liquid process wherein raindrops form by the merging of the cloud droplets (Bowen, 1950; Ludlam, 1951; Young, 1975). This mechanism proceeds most rapidly in clouds having a high liquid water content (LWC) and a broad spectrum of cloud drops. The sources and characteristics of atmospheric aerosol particles capable of forming drops large enough to initiate the coalescence mechanism are largely unknown and the subject of much research. Typical conditions for the formation of collision-coalescence rain are (a) convective clouds with bases warmer than about +15°C and accompanying large LWC and (b) stratified clouds of sufficient lifetimes that are too warm to initiate ice particles on the existing IN. Coalescence rain occurs when drops grow large enough to fall to the Earth before they are carried by the updraft to levels cold enough to cause them to freeze.

The so-called Bergeron (1935) mechanism—or cold-cloud mechanism—postulates the nucleation of ice particles in supercooled clouds followed by their growth by vapor diffusion into snow particles. Under favorable conditions they may aggregate as snow or rime to form low-density graupel or snow pellets. This mechanism was first postulated by Bergeron,[1] building on earlier work by Alfred Wegener, and developed into a conceptual model of precipitation by Findeisen (1938). The sources and characteristics of natural IN are largely unknown. In general this mechanism may be important in clouds of all types where temperatures are colder than about –15°C, including the upper parts of cumulonimbus clouds at all seasons and latitudes. It accounts for most wintertime snow.

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[1] Bergeron first gave his paper before the Lisbon meeting of the International Union of Geodesy and Geophysics on September 19, 1933, but it was not published until 1935.

Ice may also form in clouds through the freezing of drops. It is well established that the probability of drop freezing is inversely proportional to temperature and directly proportional to drop size. Thus, large drops are more likely to freeze at warmer temperatures than smaller ones. The nature and concentrations of nuclei capable of inducing drop freezing (freezing nuclei, FN) are largely unknown and the subject of current research. A variant of the warm rain mechanism—sometimes called the coalescence-freezing mechanism—comes into play in clouds having both an active coalescence mechanism and an updraft strong enough to carry drizzle drops upward to levels where they freeze through the action of FN. In many situations this may occur at temperatures as warm as –5°C to –10°C. Upon freezing, the drizzle drops become small ice pellets. Further growth through riming with cloud drops produces high-density graupel and small hail. These particles then melt into raindrops upon descending below the 0°C-level. This mechanism appears to be very important in convective clouds having bases warmer than about +15°C and with low sub-cloud CCN concentrations.

Under certain cloud conditions the process of riming may result in the creation of small ice particles (so-called secondary ice particles, SIP) in numbers vastly exceeding the original number of ice nuclei. Although the details of this process are still a matter of research, this mechanism may be very important in natural precipitation. The occurrence of SIP was first elucidated from physical measurements obtained in a scientific cloud-seeding experiment, and is still the subject of research (Hoffer and Braham, 1962; Koenig, 1963; Braham, 1964, 1986a; Hallet and Mossop, 1974).

Cloud physicists now have relatively clear pictures of the physics involved in these three precipitation mechanisms. It is possible that the majority of clouds of all types represent more complex situations, but conceptual cloud-seeding models usually are based on one of these three models.

FIRST EXPERIMENTS AND FIRST CONTROVERSIES

In the mid–1940s laboratory and field experiments by Drs. Vincent Schaefer, Irving Langmuir, and Bernard Vonnegut of the General Electric Laboratory demonstrated that dry-ice and silver-iodide smokes were excellent ice nucleants, and that when released into supercooled stratus clouds, the treated regions were gradually converted into large numbers of tiny ice crystals. These demonstrations appeared to give strong support for the Bergeron mechanism. Even at the time of the 1946–1947 experiments it was well known that the clouds used in those demonstrations contained so little water that even if all of it reached the ground, the amount of rain (or snow) would be insignificant. Meteorologists were aware that useful amounts of precipitation required deep cloud layers with updrafts and continued inflow of moist air, and that natural precipitation results from a progression of and complex interactions between microphysical processes and cloud dynamical processes.

The unbridled enthusiasm of Dr. Langmuir for what might be possible through cloud seeding and the potential legal liability implications of the early experiments led the General Electric Company to discontinue field experiments, and in 1947 to negotiate a contract for further fieldwork to be carried out by the military, with Dr. Langmuir and

Dr. Schaefer as technical consultants. This effort came to be called Project Cirrus (Havens et al., 1978). The results of Project Cirrus were widely distributed and the participants were not shy in reporting the potential of cloud seeding. Dr. Langmuir was a world-renowned scientist, and his speculations as to what might be accomplished by seeding clouds commanded attention. By this time collision and coalescence were recognized as important for producing rain; combined with Langmuir's chain reaction theory, which deems good collection efficiencies as necessary for inducing precipitation from warm clouds (Langmuir, 1948), it is not surprising that some scientists and large numbers of the populace accepted the proposition that seeding of clouds might increase rainfall and also perhaps mitigate the vagaries of severe weather. The combination of a few overly enthusiastic scientists, an active press, and a receptive populous (especially in drought-prone areas) quickly resulted in a worldwide commercial industry devoted to cloud seeding, and an era of great interest and concern among governmental and scientific organizations.

These early days of cloud seeding were described by J. C. Oppenheimer of the Advisory Committee on Weather Control (ACWC, 1957) as follows:

> Within two years after Langmuir's and Schaefer's historic experiment in 1946 of seeding clouds with dry ice, and the beginning of governmental research, a number of commercial cloud-seeding companies were organized. Exorbitant claims by some seeding organizations and scientists led to sharp differences of opinion as to the economic benefits of seeding activities. Various aspects of this controversy came to the attention of Congress. Between 1951 and 1953, Congressional hearings on several bills dealing with cloud seeding revealed that farmers, ranchers, electric utilities, municipalities and other water users were paying 2 cents to 20 cents per acre, and annually were spending between $3 million and $5 million on weather modification activities covering approximately 10 per cent of the land area of the nation. ...As a result of this lengthy consideration, the Advisory Committee on Weather Control was established by an Act of 13 August 1953.

Findings of this committee are considered below. Other details of the history of these early days of cloud seeding can be found in Byers (1974), Elliott (1974), and McDonald (1956).

AN EMERGING INDUSTRY AND DEVELOPING PUBLIC CONCERN

Initial cloud-seeding experiments were conducted from airplanes flying in or slightly above the cloud target. With the subsequent development of devices for releasing silver iodide particles from ground generators, the cost of seeding operations became quite nominal. This led immediately to widespread efforts to increase rain by operating ground generators upwind of the target areas.

With low unit costs and the implicit assumption that cloud seeding could do no harm, and at the worst would be ineffective, the industry grew almost overnight. The commercial operations were paralleled by programs in the Bureau of Reclamation (which was to become a major supporter of weather modification studies), the Weather Bureau, the Department of Defense, and others. Almost immediately cloud-seeding programs sprang up in Australia, France, Israel, and South Africa. There also was a renewed interest in hail suppression in Alpine countries where such programs were already under way. By 1951 weather modification programs were active in about 30 countries.

In the confident belief that seeding would produce a positive effect (such as an increase in rain or decrease in hail), project sponsors required the commercial operators to seed every available opportunity. In commercial operations there was no room for randomization of cloud treatments. Many projects lasted only one or two seasons. Few if any made provision for measuring the physical variables associated with rain formation in their seeded clouds. As a result rigorous proof of a seeding effect in the commercial cloud-seeding projects was very difficult at best, and generally not possible.

The commercial seeding operators provided reports to their sponsors. These reports typically contained an estimate of the seeding effects, usually based on comparison with a pre-seeding period, perhaps with a nearby area not used in their project. The inability of commercial operators to demonstrate positive seeding effects beyond a shadow of doubt gradually led to a skepticism and demand for more convincing evidence. In a number of hail suppression programs a reduction in damage claims led insurance companies and farmers to continue seeding. Nevertheless, the number and volume of commercial projects began to decline. By about 1956–1957 it had reached a level of about one-fourth of its peak.

The rapid expansion of the seeding industry, with claims of seeding effects that could not be rigorously substantiated and for which there was only a sketchy theory and questionable physical evidence, deepened the split between meteorologists and those supporting the seeding efforts. A few of the commercial companies, however, made an effort to deal openly with these problems. These companies survived and contributed substantially to increased knowledge about the seedability of clouds. Yet even today the words “weather modification” and “cloud seeding” conjure up images of alchemy and charlatans.

THE PIONEERING EXPERIMENTS

In the early 1940s most meteorologists had little background in the physics and chemistry of cloud particles, but some of those who entered the field from other physical and engineering sciences during the wartime training programs saw the possibility that cloud seeding might prove useful as a tool for probing the inner workings of clouds. Recognition of the great potential benefits that might accrue from proven weather modification techniques prompted the Weather Bureau and scientific research units in the U.S. Army, Navy, and Air Force to consider experiments to clarify the potential for cloud seeding. In 1947 the Weather Bureau launched its Cloud Seeding Project, which included 176 non-randomized airplane releases of dry-ice pellets into the tops of supercooled stratified clouds over Ohio and the Sierra Nevadas and into convective clouds over Ohio and along the Gulf Coast. Results were inconclusive.

One of the early experiments, organized in 1951, was the Artificial Cloud Nucleation Project (Petterssen, 1957). Results of randomized seeding were generally inconclusive, except for showing that water spray seeding of tropical cumuli speeded the onset of precipitation. Subsequent studies suggested that total precipitation from these clouds may have been decreased, because the seeding and earlier onset of precipitation shortened the time available for creation of cloud water (Braham et al., 1957). Other projects followed, with meteorologists joined by chemists, physicists, and engineers, and with generous support from the Departments of Defense, Interior, and Commerce and the National Science Foundation (NSF). Under the umbrella of cloud seeding, scientists mounted field and laboratory efforts that led to a breathtaking increased understanding of the microphysics and dynamics of clouds. In an effort to put cloud seeding on a more rigorous foundation, several university and government groups launched major studies of clouds and their reaction to seeding.

Some of the most productive studies during this period included randomized seeding trials with accompanying physical measurements using the most modern tools available at the time. Measurements were made in both seeded and non-seeded clouds. Some of these experiments were "double blind," such that the group conducting the seeding did not collect and analyze the rainfall data, while those involved in the analysis had no knowledge of when and where seeding had taken place (e.g., the Missouri Project Whitetop). Typically these experiments ran for several seasons. Results were mixed. None of these experiments provided incontrovertible evidence that seeding was effective; many suggested rainfall increases (or hail decreases) from seeded clouds, but a few suggested rainfall decreases. They suggested, but did not prove, that any change in precipitation resulting from seeding would likely be limited to several percent, much less than the original claims by some non-scientific operations.

The programs of physical measurements greatly expanded knowledge about cloud processes and led to a number of important scientific findings: demonstration of the power of numerical modeling of targeted seeding of cumuli; realization that the coalescence mechanism operated in warm season clouds in mid-latitudes and was not restricted to the tropics; and that drizzle drops that had formed by coalescence often froze and began growth by riming at temperatures as warm as –5°C to –10°C (this led to the recognition of a coalescence-freezing mechanism, and in some conditions the production of secondary ice particles). There were early suggestions that the latent heat released by seeding-induced freezing of liquid cloud water could prolong the life of the cloud, leading to more rain than would otherwise have been delivered. These and other observations led to the possibility that increases in cloud downdrafts and sub-cloud outflow caused by seeding may prolong the lifetime of the cloud complex as a whole, although the exact mechanisms for this continue to be unknown.

THE NEED FOR IMPARTIAL ASSESSMENT OF SEEDING RESULTS

The rapid growth of the commercial cloud-seeding industry, extravagant claims of seeding effects from some commercial operations, and the inherent weaknesses in their assessments raised widespread concern. Thus, the National Academy of Sciences (NAS), the NSF, the American Geophysical Union, and the American Meteorological Society

(AMS) all undertook in-depth examinations of cloud seeding. Papers on cloud physics began to appear at scientific meetings. Entire conferences were devoted to the subject, and many of these became the battleground between seeding proponents and opponents. In virtually every case there was a plea for basic research to enhance scientific understanding of cloud processes as a prerequisite for intelligent cloud-seeding operations.

There was a movement toward independent assessment of the reports of commercial cloud-seeding operations. This involved analyses (or reanalyses) of project findings by persons not involved in the original project and if possible using data collected independently from the original project. The first such assessment was conducted by the President's ACWC. Captain Howard T. Orville, USN (ret.), chaired this committee, and its final report was submitted to the President in December 1957 (ACWC, 1957). The ACWC hired climatologist-statistician Herbert Thom and assisted by a group of outstanding statisticians to conduct an independent assessment (reanalysis) of 12 short-term commercial silver-iodide seeding operations. They concluded that winter-season west-coast orographic precipitation was increased an average of 14 percent, significant at the 99 percent level (α=0.01). But operations in other seasons and areas did not give conclusive evidence for a seeding effect. The ACWC made a strong plea for increased support of those sciences that were basic to understanding clouds and cloud systems.

In 1963 the NAS appointed a Panel on Weather and Climate Modification to "undertake a deliberate and thoughtful review of the present status and activities in this field, and of its potential and limitations for the future." The panel, chaired by Gordon J. F. MacDonald, issued a preliminary report in 1964 (NRC, 1964) in which it concluded that

> it has not been demonstrated that precipitation from winter orographic storms can be increased significantly by seeding….We conclude that the initiation of large-scale operational weather modification programs would be premature. Many fundamental problems must be answered first. It is unlikely that these problems will be solved by the expansion of present efforts, which emphasize the a posteriori evaluation of largely uncontrolled experiments. We believe that the patient investigation of atmospheric processes coupled with an exploration of the technological applications will eventually lead to useful weather modification, but we must emphasize that the time-scale required for success may be measured in decades.

The panel's final report (NRC, 1966) included a number of recommendations concerning the support and infrastructure needed for research in weather modification. It also sponsored two independent evaluations of a small number of commercial seeding operations. Concerning their reanalysis of 14 short-duration, ground-generator operations in the eastern United States, they found indications of a positive seeding effect. However, "results of these fourteen projects…cannot by themselves be regarded as conclusive evidence of the efficacy of seeding; yet taken together they seem to us to be a new indication of positive effect, warranting optimism." The panel also sponsored an analysis using seasonal runoff data as the test variate in four west-coast winter-season orographic seeding operations totaling 41 years of operations. It found overall runoff increases of about 12 percent, statistically significant at the 96 percent level (α=0.04).

The NSF issued a series of annual reports on weather modification research and evaluation between 1959 and 1964. In 1964 the National Science Board appointed a Special Commission of Weather Modification, chaired by Dr. A. R. Chamberlain, which found that "supercooled fog on the ground can be dissipated. No practical approach to the dissipation of warm fog is at hand." Also, "while the evidence is still somewhat ambiguous, there is support for the view that precipitation from some types of clouds can be increased by the order of ten percent by seeding. If the results are confirmed by further studies they would have great significance. The question of corresponding decreases of precipitation outside the target area is unresolved." It suggests that "advanced experimental techniques and application of sophisticated concepts in statistical design promise to reduce the present uncertainty in the interpretation of field experiments" (NSF, 1965).

In 1973 the NAS Review Panel on Weather and Climate Modification (T.F Malone, chair) issued a report titled "Weather and Climate Modification, Problems and Progress." Based on the results of several randomized experimental seeding programs conducted after the 1966 NAS report, the panel concluded that

> ice-nuclei seeding can sometimes lead to more precipitation, can sometimes lead to less precipitation, and at other times…have no effect….It is concluded that the recent demonstration of both positive and negative effects from seeding convective clouds emphasizes the complexity of the processes involved….A more careful search must be made to determine the seedability criteria that apply to the convective clouds over various climatic regions….The Panel concludes that there is a pressing need for further analyses of the areal extent of seeding effects under a variety of meteorological and topographical situations and for investigations into the physical mechanisms that are responsible for any such effects.

Concerning hail reduction and mitigation of severe weather hazards, the panel noted the need for further research (NRC, 1973).

Even before these reports were published, papers appeared in the scientific literature pointing to sources of bias and other technical problems that had not been considered that could invalidate conclusions. If anything, the split between those who believed in the immediate application of cloud seeding and those who believed that such actions were premature only widened and deepened.

In response to the National Weather Modification Act of 1976 (PL 94-490) the Secretary of the Department of Commerce appointed the Weather Modification Advisory Board, chaired by Harlan Cleveland, to take an in-depth look at cloud seeding. Its two-volume final report was submitted in 1978. That committee found that the major task ahead was to learn more about the atmosphere and processes within it. To this end it urged an increase in federal support for meteorology and other sciences important to this effort. Concerning the status of cloud seeding the Committee found that

> the experimental evidence for cloud seeding has not yet reached the levels of objectivity, repeatability, and predictability required to establish new knowledge and techniques. There are, however, several lines of evidence suggesting that carefully controlled seeding, using means appropriate to the aims, will result in weather modification effects of useful dimensions. [Vol. 1, p. 35.]

Several assessments of individual seeding projects, or groups of projects, have been made by individual scientists familiar with cloud physics and cloud seeding but not directly involved with the projects they assess. Generally speaking, these authors came to the view that cloud-seeding experiments have not yet provided the evidence required to establish scientific validity, though the prospects are promising and worth pursuing.

After due consideration our Committee finds little reason to differ from these findings. This is due in part to the lack of concerted research in weather modification. It has been three decades since the last NRC report on weather modification. In the interim there have been improvements in the understanding of cloud processes and significant development of tools and techniques, including computational power, statistical analyses, and remote sensing of cloud systems. These opportunities mandate a fresh look at the status and potential of weather modification.

2

Current Status of Weather Modification Operations and Research

CURRENT OPERATIONAL EFFORTS

In the annual register of National Weather Modification Projects, compiled and published by the World Meteorological Organization (WMO), 24 countries provided information on more than 100 ongoing weather modification activities in 1999 (Plate 2), with most of the precipitation enhancement programs located in the subtropical semiarid belts on either side of the equator. These data, however, pertain only to countries that report such information, and at least 10 other countries were conducting weather modification programs. A few of these precipitation enhancement and hail suppression programs have been conducted on a continuous basis for more than 40 years. China is the most active country in pursuing weather modification, with an investment estimated at more than $40 million annually, both for hail suppression and precipitation enhancement.

In the United States the number of precipitation enhancement and hail suppression programs has varied over the course of the past several decades, while the number of fog dissipation projects has remained nearly constant throughout this time (with the primary example being the program sponsored by Delta Airlines at Salt Lake City International Airport). In the last few years there has been an increase in operational weather modification activities in the United States, with approximately 66 programs (for hail suppression and snow or rain enhancement) being conducted in 2001, according to activities reported to NOAA (Plate 2). All of these projects are located in the southern and western states of the United States and are sponsored by local, state, or private entities. No federal funding currently supports any project.

The increase in operational programs over the past 10 years indicates a growing perceived need for enhancing water resources and mitigating severe weather in many parts of the world, including the United States. For users and operators of weather modification technologies, the decision of whether to implement or continue an operational program is a matter of cost-benefit risk management, which raises questions about what constitutes “successful” modification. Cloud-seeding experiments have shown mixed results, but many operational cloud-seeding programs continue, based on what is seen as circumstantial or indirect evidence of positive results. For instance, studies of hail-damage insurance claims in North Dakota over a seven-year period show a 43 to 45 percent reduction in claims in counties where hail suppression is carried out (Smith et al., 1997). Studies of rain enhancement programs in this state report up to a 15 percent increase in rainfall (Johnson, 1985) and up to a 5.9 percent increase in wheat yields (Smith et al., 1992). Indirect qualitative assessments of the additional water produced from the Utah operational programs described by Griffith (1991) indicated costs in the range of a few dollars per acre-foot (Stauffer and Williams, 2000). The Tasmanian program calculated a cost-benefit ratio of 13 to 1 (Ryan and King, 1997). These results are viewed as a beneficial for hydropower energy production (Cotton and Pielke, 1995).

There is little or no research associated with any of these operational programs, which highlights the need for intensive studies to further develop a scientific basis for weather modification technology. Many current precipitation enhancement projects, particularly in developing countries, use old technology and lack the latest instruments and other operational tools. The use of modern observational tools, models, experimental design techniques, and statistical evaluation techniques are prerequisites for shedding light on cause-and-effect relationships.

CURRENT SCIENTIFIC EFFORTS

Currently there are very few weather modification research programs in the world. As discussed in Chapter 1, research in weather modification was actively pursued after the initial discoveries in the late 1940s and peaked in the late 1970s, when funding in the United States alone was around $20 million per year. This amount dwindled after 1980 to less than $500,000 per year and has continued to decline in recent years. A few research projects on a smaller scale have continued in the United States and several other countries, including South Africa, Thailand, Mexico, Argentina, Israel, Japan, and the United Arab Emirates. In the following sections and in Appendix A, the status and current scientific understanding of various aspects of weather modification are reviewed.

Precipitation Enhancement

Weather modification research requires the involvement of a wide range of expertise due to the multifaceted nature of the problem and the large range of scales that are addressed. The chain of events in precipitation development ranges from at least the mesoscale dynamics determining the characteristics of the cloud systems down to small-scale microphysics determining the nucleation and growth characteristics of water droplets and ice particles (e.g., see Pruppacher and Klett, 1998; Braham, 1979, 1986b; Dennis, 1980; Rogers, 1976). Our knowledge of the individual steps in this chain has increased significantly in the past 20 years, but major gaps still exist in our understanding of certain physical processes. Although most rainfall enhancement experiments focus on modifying the microphysical aspects of clouds, it is important to emphasize that cloud microphysical and dynamical processes are intimately linked, and that the major controls on precipitation occurrence and amounts are the mesoscale and larger-scale atmospheric dynamics (e.g., see Cotton and Anthes, 1989; Vali et al., 1988). At present, however, no theoretical framework or experimental methodology exists that could support any intentional modification of the atmosphere on these larger scales (see Chapter 4).

Precipitation enhancement from mixed-phase clouds (i.e., clouds or parts of the clouds containing temperatures below 0°C) has been the focus of most weather modification research and operations around the world. The microphysics and dynamics of these cloud systems are complex and, especially in the case of convective storms, are characterized by large natural variability. Establishing cause-and-effect relationships through the complete chain of events leading to precipitation formation is extremely challenging. Glaciogenic seeding material (see also Chapter 1) is the most common seeding material used for precipitation enhancement. Hygroscopic seeding material, such as salt powders, also has been used but has generally proved to be less attractive than glaciogenic seeding material. During the past decade, however, tests have been conducted on mixed-phase clouds using small (sub-micron to tens of microns in diameter) hygroscopic particles released by pyrotechnic flares. The results of glaciogenic and hygroscopic precipitation enhancement techniques are distilled in the following section (see Box 2.1 for a summary), and the detailed methodology is presented in Appendix A.

Glaciogenic Seeding Experiments

Based on the quantity of glaciogenic seeding material used to enhance ice content, two seeding concepts have historically been proposed and widely referred to as “static” and “dynamic” seeding. In the static seeding concept the aim is to capitalize on the less-than-optimal ice crystal concentrations often present in nature, which leads to prolonged periods of supercooled water, especially in orographic clouds. These regions of supercooled water have to exist for a sufficient length of time for ice crystal growth and precipitation to occur. In the dynamic seeding concept the emphasis is on the release of latent heat by rapid freezing, which enhances buoyancy and invigorates cloud growth, thereby increasing precipitation production. It should be noted that these concepts are not mutually exclusive because they both result in increased ice crystal concentrations and affect cloud dynamics. The same seeding material is used in both seeding concepts and only the quantity of seeding material is varied. While the dynamic seeding concept is primarily applicable to convective clouds, the static seeding concept has been widely utilized in orographic and layer-type clouds as well as in convective clouds. In convective clouds, both “static” and “dynamic” responses can occur in a mutually interactive fashion (Rosenfeld and Woodley, 1993).

Static Seeding: Convective Clouds

The top half of Table 2.1 lists examples of static glaciogenic seeding experiments designed to test whether precipitation can be increased in convective clouds in response to seeding with ice nucleating agents. For static seeding of convective clouds, statistically significant rainfall increases were not obtained or, in the case of the Israeli experiments, continue to be debated (Gabriel and Rosenfeld, 1990; Rosenfeld and Farbstein, 1992; Rangno and Hobbs, 1995; Rosenfeld and Nirel, 1996; Levi and Rosenfeld, 1996). In each

TABLE 2.1 Examples of Static Glaciogenic Seeding Experiments in Precipitation Enhancement

Type of cloud	Experiment	Reference
Convective clouds	Arizona projects	Battan and Kassander, 1967
	Israeli experiments	Gagin and Newmann, 1974
	Project Whitetop	Braham, 1964, 1979
	High Plains Experiment (HIPLEX) 1	Smith et al., 1984
Winter orographic clouds	Lake Almanor experiment	Mooney and Lunn, 1969
	Sierra Cooperative Pilot Project (SCPP)	Reynolds and Dennis, 1986; Deshler et al., 1990; SCPP, 1982
	Climax I and II	Grant and Mielke, 1967; Mielke et al., 1981
	Bridger Range experiment	Super and Heimbach, 1983; Super, 1986
	Tasmanian experiments	Ryan and King, 1997

case, however, useful results or guidance was obtained which contributes to the current knowledge base in weather modification. Among these results are:

- that physical measurements in clouds are essential to provide an understanding of the underlying processes;
- that high concentrations of ice crystals occur naturally in some cumulus clouds at temperatures as warm as –10 °C thus allowing rapid production of precipitation particles;
- that the window of opportunity for enhancing rainfall from a given cloud (system) is limited;
- that treatment can both enhance and reduce rainfall; and
- that results based on small clouds might not be transferable to dynamically more vigorous and larger cloud complexes.

Static Seeding: Winter Orographic Clouds

In the case of static seeding of winter orographic clouds (bottom of Table 2.1), important results include:

- recognition of the complex interactions between terrain and wind flow in determining regions of cloud liquid water and, later, through microwave radiometer measurements, the existence of a layer of supercooled water;
- acknowledgment of the need to target and track the dispersion of seeding material and, again later, the demonstration of complex flow including ridge-parallel flows below the ridge crest exist in pronounced terrain;
- evidence of marked increases in ice particle concentrations leading to increased precipitation depending upon the availability of supercooled liquid water;
- re-emphasis of the need for physical data that can be used together with numerical models to identify the spatial and temporal changes in cloud structure;

- development of highly efficient silver chloro-iodide ice nuclei and other fast acting, highly efficient ice nucleating pyrotechnic and generator devices (Fig. 2.2); and
- development of methods to detect traces of seeding agents in snowpack and rain water.

Dynamic Seeding

Table 2.2 lists four examples in which glaciogenic seeding was used in the expectation that an increase in cloud buoyancy would follow freezing of supercooled water drops. The intent was to seed supercooled clouds with large enough quantities of ice nuclei (100–1000 cm^{-3}) or coolant to cause rapid glaciation. Increased buoyancy was expected to cause the cloud to grow larger, ingest more water vapor, and yield more precipitation. It was postulated that increased precipitation would enhance downdrafts and outflows which, in turn, would initiate new convection and extend the effects of treatment (Woodley et al., 1982). Few of the hypothesized steps in the chain of events have been measured in experiments or validated by numerical models (Orville, 1996). However, as in the case of static seeding, dynamic seeding has contributed significantly to our current store of knowledge. Among the findings and results from dynamic seeding experiments that contribute to the current state of knowledge in weather modification are:

- the complexities of ice formation in clouds where ice and supercooled water have been found at temperatures as high as –10°C and as low as –38°C, respectively (Rosenfeld and Woodley, 2000);
- the dependence of ice formation upon CCN concentrations and sizes (e.g., freezing of large drops) and the role of primary and secondary ice formation in graupel production which have emerged from these experiments are areas of uncertainty;
- the importance of coalescence (and hence aerosols) on cloud structure, evolution and rain production (Rosenfeld and Woodley, 1993; Johnson, 1987);
- the importance and relationship between cloud dynamics and microphysics and the induced changes resulting from seeding; and
- the power and limitations of existing radar systems (Chapter 4) as integral experimental tools and as possible means of verification of seeding results.

TABLE 2.2 Examples of Dynamic Glaciogenic Seeding Experiments in Precipitation Enhancement.

Experiment	Reference
Florida Area Cumulus Experiments (FACE) 1 and 2	Woodley et al., 1982; Woodley et al., 1983; Gagin et al., 1986
Texas experiments	Rosenfeld and Woodley, 1993
South African experiments	Bruintjes et al., 1987; Krauss et al., 1987
Thailand experiments	Woodley et al., 1999

Hygroscopic Seeding Experiments

Hygroscopic seeding, as opposed to glaciogenic seeding, is directed at promoting the coalescence of water droplets in the cloud. The intention is to promote particle growth through coalescence and thereby improve the efficiency of the rainfall formation process. Appropriately sized salt particles, water droplets from sprays of either water or saline solution (Bowen, 1952; Biswas and Dennis, 1971; Cotton, 1982; Murty et al., 2000; Silverman and Sukarnjanasat, 2000), and hygroscopic flares (Mather et al., 1997; WMO, 2000) have been used. Statistical results, observations and modeling results for large (>10 μm diameter) have provided some statistical evidence (Murty et al., 2000; Silverman and Sukarnjanasat, 2000) and evidence that under certain conditions with optimal seed drop size spectrums, precipitation can be enhanced (Farley and Chen, 1975; Rokicki and Young, 1978; Young, 1996). The hygroscopic flare particle seeding experiments have provided statistical support for rainfall increases due to seeding based on single cloud analyses, but the physical processes leading to these increases in precipitation are not well understood. Despite the wide use of hygroscopic seeding, the results have been inconclusive due to a lack of physical understanding and, in some cases, inconclusive statistical evaluations.

Table 2.3 lists examples of field experiments or operations in which hygroscopic seeding was employed. Among the results from these programs that have contributed to the current state of knowledge in weather modification are:

- that both the South African and Mexican experiments produced remarkably similar statistical results in terms of the differences in radar estimated rainfall for seeded versus non-seeded groups (Plate 3) (Bigg, 1997; Silverman, 2000; WMO, 2000);
- that in the South African and Mexican experiments, reevaluation of the results showed an increase in rain mass 30–60 minutes after seeding, significant at the 96 percent level ($\alpha = 0.04$) or higher;
- that marked differences in concentrations of ice particles were found in maritime clouds (high) versus continental clouds (low) signifying the active role of collision and coalescence in maritime clouds compared to continental clouds (Scott and Hobbs, 1977; Cotton, 1972; Koenig and Murray, 1976);
- that freezing temperatures increased with increasing drop size because larger droplets contain or have a higher probability of colliding with ice nuclei;
- that relatively large droplets (>24 μm) played a role in ice multiplication processes, including mechanical fracturing during melting and evaporation and ice splinter formation during riming (Hallet and Mossop, 1974);
- that a delayed response in radar-derived storm properties was a possible function of seeding-induced dynamic processes beyond the classical cloud physics results that links cloud condensation nuclei and droplet spectra to rain production (WMO, 2000); and
- that hygroscopic seeding might overcome inhibiting effects on rainfall of air pollution (Rosenfeld et al., 2002).

TABLE 2.3 Examples of Hygroscopic Seeding Experiments in Precipitation Enhancement

Experiment	Reference
South African experiments	Mather et al., 1997
Indian experiments	Murty et al., 2000
Thailand experiments	Silverman and Sukarnjanasat, 2000
Mexico experiments	WMO, 2000

Hail Suppression

Hail suppression programs are driven by the severe impacts of hail on many different sectors of the economy. In recent years hail damage to crops in the United States typically has been around $2.3 billion annually (Changnon, 1998). Susceptibility to

BOX 2.1
Summary of Cloud-Seeding Techniques for Precipitation Enhancement

Glaciogenic Seeding: Seeding of clouds with appropriate ice nuclei (e.g., silver iodide) or cooling agent (e.g., dry ice, liquid propane) to create or enhance the formation of ice crystals, particularly the conversion of supercooled water to ice. The two general approaches are

1. Static seeding, which focuses on microphysical processes; creation of ice crystals and particles; enhances graupel and snow production by increasing the number of ice particles and triggering precipitation process earlier in the cloud's lifetime. *Examples: Climax I and II; Israel; Project Whitetop.*

2. Dynamic seeding, which increases buoyancy of cloud by converting supercooled liquid drops to ice. The subsequent release of latent heat of fusion increases cloud buoyancy, cloud lifetime, and rain production. *Examples: FACE I and II; Texas.*

Hygroscopic Seeding: Enhance rainfall by seeding clouds with appropriately sized salt particles or droplets, promoting the coalescence process.

1. Large hygroscopic particle seeding, which seeds clouds with large salt particles (e.g., >10 μm dry diameter) to short-circuit the condensation growth process and provide immediate raindrop embryos to start the coalescence process. *Examples: Project Cloud Catcher, India, Thailand.*

2. Hygroscopic flare seeding, which focuses on broadening the initial drop spectrum during the nucleation process by seeding with larger than natural CCN (0.5 μm to 3 μm dry diameter) to enhance the coalescence process in warm and mixed-phase clouds. *Examples: South Africa, Mexico experiments.*

damage depends on the crop type, its stage of development, the size of the hail, and the magnitude of any wind accompanying the hail.

Any theory of hail growth that is complete enough to serve as the basis for suppression must include at least the following elements: (1) hail embryo formation process, including the microphysics of particle growth and the region or regions in the storm where such growth occurs; (2) transport of embryos to regions of abundant supercooled liquid water where the further growth to hail is possible; (3) growth trajectory of the hailstone itself as it passes through the strong updraft of a storm; and (4) the time evolution of the storm's updraft and cellular development. Such processes and variables as ice nucleation, dominant rain formation, cloud-base temperature, environmental wind shear, and updraft strength and width are also essential elements of hail formation.

Sulakvelidze et al. (1974), attempted to combine these elements in a unified theory of hail formation. Subsequent work showed the complexity of hail producing convective storms ranging from the "ordinary" through severe multi-cell storms to supercell storms (Browning and Foote, 1976; Browning et al., 1976; Foote and Knight, 1977). Radar measurements, including multi-Doppler, and aircraft studies have produced hail growth trajectories within the measured storm velocity fields (Foote, 1985). None of these or other studies have provided an adequate description of the essential elements of hail formation. Advocates of hail suppression programs claim positive results based upon reported reductions in crop-hail insurance losses (e.g., 45 percent in the study of Smith et al., 1997 and 27 percent in the study of Eklund et al., 1999). However, natural variability in crop-hail insurance losses from season-to-season and an apparent long-term decline beginning around 1950 in hail losses (Figure 2.1) make these data difficult to interpret unambiguously.

Numerical models of storms can be a useful vehicle for testing hail theories. They provide a self-consistent environment for computing hail growth and liquid water depletion. Indeed, much has been learned about the dynamics of storms using cloud models (e.g., Weisman and Klemp, 1982, 1984). However, as discussed in Chapter 4, models powerful enough to include the details of the dynamics and microphysics in three dimensions still do not exist. Such sophisticated models (e.g., bin-mixed-phase, microphysics with full aerosol interactions) are feasible with computer resources commensurate with those currently supporting climate simulations.

Other Severe Weather Phenomena

Lightning

Cloud-to-ground (CG) lightning has been a major cause of fires in man-made structures and in forests, and it has been the cause of many human deaths. While lightning protection has been a topic of study for several centuries and numerous technologies have been developed (AMS, 1998), studies on lightning suppression or the modification of lightning characteristics by inadvertent or advertent intervention has only

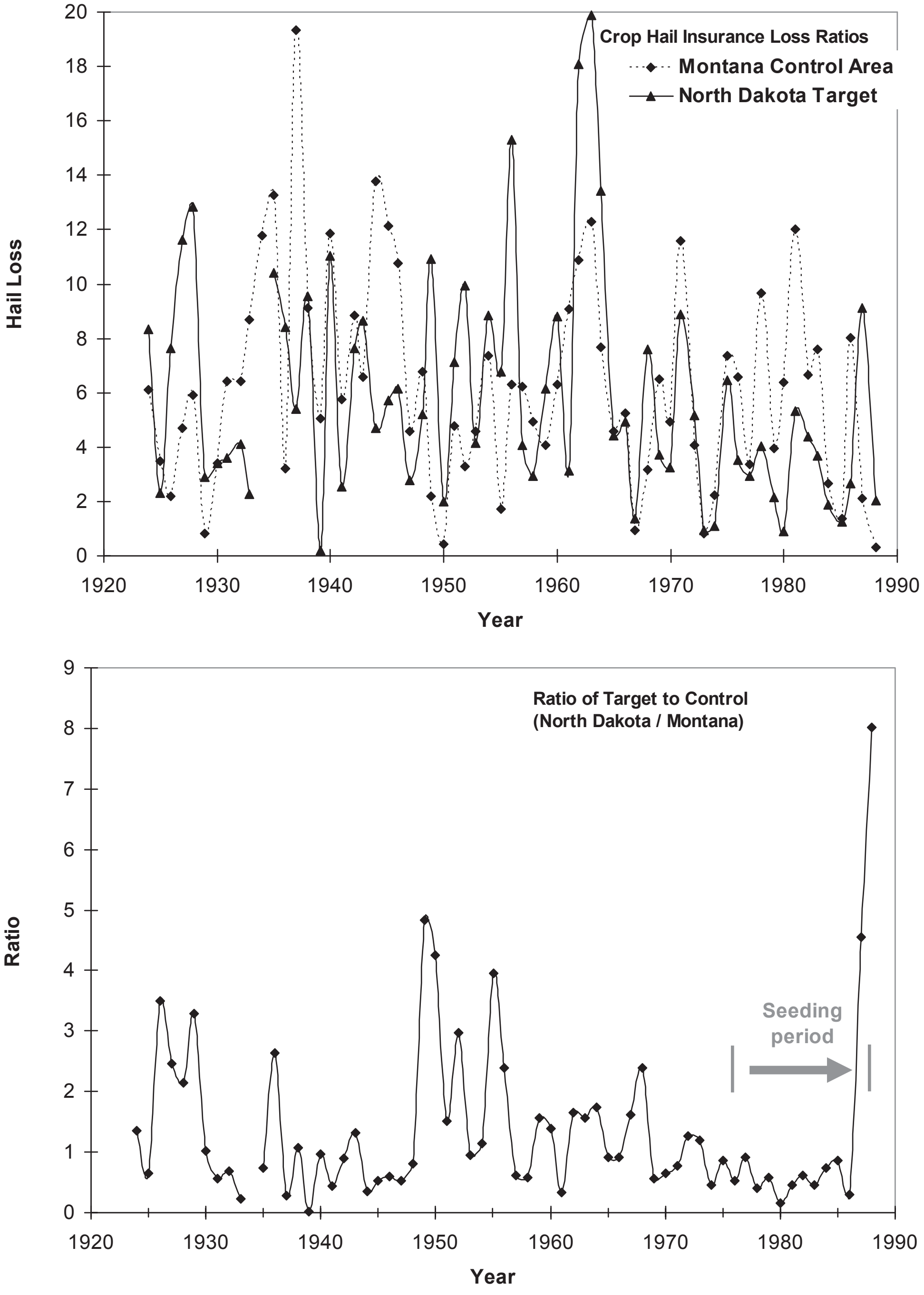

FIGURE 2.1 Results from an operational hail suppression program in North Dakota with hail losses—the unitless ratio of insurance damage claims paid from hail events to the total insured liability—reported in two adjacent areas. From Smith et al., 1997, the upwind Montana area was treated as a control for the North Dakota area in which hailstorms had been seeded. During the heavily seeded years of 1976–1988, the seeded area shows proportionally less hail than the control area. However, the ratio of the two hail loss curves (shown in the bottom figure) indicates this trend started as early as 1950. SOURCE: B. Foote, adapted from Smith et al., 1997.

recently come to the foreground. Lyons et al. (1998) reported that lightning-producing storms that ingested smoke from biomass burning displayed altered electrical characteristics. Smoke-affected storms had an anomalously large fraction of positive cloud-to-ground lightning strikes, probably due to changes in microstructure of the clouds. In North America most wildfires are initiated by lightning, but most negative cloud-to-ground strokes are of short duration, providing insufficient time for igniting biomass fires (Fuguay et al., 1972). About 95 percent of positive strokes are of long enough duration to ignite fires (Pyne et al., 1996) and could possibly also have adverse impacts on engineered structures. In clouds unaltered by smoke CCN only about five percent of CG lightning flashes are positive strikes. Hence, if there is an increase in frequency and duration of wildfires and their smoke, one might also expect to increase the number of lightning-initiated wildfires. Steiger et al. (2002) in a study of CG lightning anomalies (enhanced lightning frequency) over Houston, Texas, attributed the increased frequency of lightning to the possible heat island effect. It also was found that increases in lightning were most pronounced when urban air pollution was highest. Houston has a strong oil refinery and automobile presence, and it is well known that oil-related industries produce large amounts of sulfur dioxide, which transforms to sulfates that are very efficient CCN. These findings appear to corroborate earlier findings of increased thunderstorm frequencies in an effluent plume in St. Louis, Missouri (Changnon et al., 1981). More recently Williams et al. (2002) proposed a conceptual model by which added smoke and other air pollution aerosols could increase the lightning activity of convective clouds. Furthermore, aerosol and cloud interactions are of central importance in these studies as in studies of the pollution effects on rainfall cited elsewhere.

There has been some interest in the suppression of lightning for the purposes of reducing lightning-induced forest fires and diminishing lightning hazards during the launch of space vehicles. The concept usually proposed involves reducing the electric fields within thunderstorms so that they do not become strong enough for lightning discharges to occur. Qualitative studies of CG lightning suppression through injecting metallic chaff into maturing cumulonimbus also have recently been suggested (Orville, 2001). A few years ago thunderstorms developed in Arizona in which one complex storm produced numerous CG and another almost none. Post analysis found that the CG-free storm complex had formed in an area where the military had been conducting chaff experiments that same day, and it was postulated that the chaff had suppressed electric fields in the storm, resulting in only in-cloud lightning production. Limited fieldwork has been done on this topic. Holitza and Kasemir (1974) and Kasemir et al. (1976) reported that using chaff seeding, they found a reduction in lightning by a factor of three for seeded versus non-seeded storms. Helsdon (1980) numerically simulated the chaff seeding in a two-dimensional cloud model. The results showed that the chaff produced large numbers of positive and negative ions, leading to a decrease in the vertical electric field in the cloud. However, these few studies are qualitative in nature and are not statistically significant due to limited evaluation capabilities at the time.[1]

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[1] Improved statistical techniques—namely Bayesian methods, which are ideal for accounting for uncertainty and providing spatial-temporal analyses (see Appendix B)—could provide more conclusive results if chaff seeding experiments were conducted again today.

The University of Florida's Lightning Research Center, the International Center for Lightning Research and Testing at Camp Blanding, Florida, and other research centers have carried out studies wherein lightning is triggered by launching a small rocket trailing a grounded wire. It has been found that lightning flashes can be triggered from clouds to ground roughly 50 percent of the time (Uman et al., 1997). Improvements in our understanding of the physics of lightning have led directly to the design and installation of lightning protection devices for a variety of electrical and electronic systems.

Hurricanes

Tropical cyclones contribute significantly to the annual rainfall of many areas, but they also are responsible for considerable damage to property and for a large loss of life. Due to increases in population density in the coastal zone of the lower 48 United States over the past 30 years, both casualties and costs due to damage and disruption are expected to continue to rise (see Table 1.1). Damage estimates due to Hurricane Floyd in 1999 exceeded $1 billion, and costs associated with evacuation equalled that number (Pielke and Carbone, 2002). Therefore, the aims of any modification procedure should be to reduce the wind, storm surge, and rain damage but not necessarily the total rainfall. Hurricane modification experiments were conducted in the 1960s and early 1970s (Project Stormfury) (Simpson and Malkus, 1964; Simpson et al., 1967; Willoughby et al., 1985), but the results were inconclusive, and there currently is no generally accepted scientific conceptual model suggesting that hurricanes can be modified (see Box 4.1).

Tornadoes

Although modification of tornados and other storms producing damaging winds is desirable for safety and cost reasons, there presently is no scientifically acceptable physical hypothesis to accomplish such a goal.

Freezing Drizzle and Rain

Speculations can be made about the possibilities of reducing aircraft icing episodes or mitigating icing of highways and roads by seeding nearby supercooled cloud regions, but there is no physical, conceptual model on how to mitigate these hazards and no work has been done in this field.

Flash Floods and Large-Scale Flooding

No physical conceptual model exists to mitigate these events and no work has been conducted in this field. If the precipitation processes were fully understood, then perhaps procedures could be designed to decrease rains from flood-producing rain clouds. Accurate numerical modeling of such conditions would be necessary for such studies.

Inadvertent Weather Modification

Human activity is inducing inadvertent effects in the atmosphere on scales ranging from the local (a given point source of pollution, urban heat island, contrails, etc.) to the global (changes in greenhouse gases and aerosols and associated cloud effects). Global effects of changes in greenhouse gases, aerosols, and cloud cover are of fundamental concern, but they go beyond the scope of this report. However, the evidence of local to regional cloud and precipitation changes due to anthropogenically derived aerosols is highly relevant to the issue of deliberate weather modification; and it is discussed below.

Aerosol effects on clouds and precipitation are a complex, multi-order problem. In 1957, Gunn and Phillips (1957) documented the detrimental effects of air pollution CCN on clouds and precipitation. Twomey (1974) then postulated that increased pollution results in greater CCN concentrations and numbers of cloud droplets, which in turn increase the reflectance of clouds. Twomey et al. (1984) argued that enhanced cloud albedo has a magnitude comparable to that of greenhouse warming and acts to cool the atmosphere. Evidence of cloud and precipitation changes due to aerosols (changes in "natural" CCN) is becoming widespread. There is ample evidence now that biomass burning and other anthropogenic sources of aerosols affect the radiative properties of clouds and precipitation processes in clouds, leading also to changes in the dynamical processes in clouds (i.e., effects on cloud lifetimes). Increased CCN lead to higher droplet concentrations and a narrower droplet spectrum (which manifests itself as a higher cloud albedo), which leads to suppressed drizzle formation and longer lasting stratiform clouds (e.g., ship-track studies, [JAS, 2000 and Albrecht, 1989]).

Recent satellite studies of cloud microstructure downwind of biomass burning and industrial pollution sources have also suggested suppressed precipitation formation in the affected clouds, as illustrated in Plates 4 and 5. (Ramanathan et al., 2001; Rosenfeld, 1999, 2000;). However, Cotton and Pielke (1995) noted that the susceptibility of the drizzle process in marine stratocumulus clouds to anthropogenic emissions of CCN may depend on the presence or absence of large and ultra-giant aerosol particles in the sub-cloud layer. In other words, the drizzle formation process is not solely regulated by the concentrations of CCN and cloud liquid water contents, but possibly also by the details of the spectrum of the hygroscopic aerosol population. In fact, Rosenfeld et al. (2002) showed that sea spray, even under light wind conditions, can restore precipitation from polluted convective clouds, doing naturally what deliberate hygroscopic seeding is attempting to achieve artificially. In addition, the intriguing evidence of increased positive lightning flashes in storms affected by smoke from the Mexican fires of 1998 is yet another example of the complex effects of aerosols on clouds, precipitation, and the microphysics relevant to cloud electrification (Lyons et al., 1998).

The effects of desert dust and mixtures with anthropogenic pollutants are important to warm rain and ice processes through their ice nucleating ability, and, possibly through the coating of sulfates, their droplet nucleating ability. The apparent decrease in rainfall in the south target area in the Israeli II study was linked by Rosenfeld and Farbstein (1992) to the incursion of desert dust. They suggest that desert dust contains more ice nuclei and also provides coalescence embryos (when coated with sulfates) that could enhance the collision-coalescence process in clouds, thus providing efficient precipitation processes in these clouds.

OTHER RESULTS

Over the past few decades there have been considerable advances in the basic sciences relevant to weather modification. For instance, through cloud modeling there is a better understanding of the microphysics of clouds and the dynamics of clouds and weather systems. More effective ice nucleants and hygroscopic nucleus flares have been developed. Progress has been made in combining cloud microphysics and cloud dynamics in three-dimensional numerical models, which give promise for better definition of where and when seeding intervention may be most effective. New tools and techniques are available for remote sensing of conditions in clouds, delineation of zones identified for seeding, tracking seeded volumes, and monitoring changes in cloud structure following seeding (as discussed further in Chapter 4). Collectively, these areas could be viewed as the scientific infrastructure of weather modification, but many of the relevant advances have yet to be applied to weather modification research.

Table 2.4 list results which have been obtained from new observing systems and laboratory and modeling studies that have not necessarily been an integral part of weather modification research over the past three decades. In each case, however, there is a direct or potential application to weather modification that has not yet been fully realized.

TABLE 2.4 Other Results Derived from New Observing Systems and Laboratory and Modeling Studies

Area of Research	Result
Aerosols	Sources and sinks
	Influence on size distribution and number concentrations of cloud droplets
	Aquatic-phase chemistry and cloud scavenging
	Aerosol-induced changes in cloud drop size spectra
	Role of pollution
Cloud droplets	In-cloud recirculation
	Physics of drop-drop collisions and collision and coalescence efficiencies
	Drop size freezing
	More universal occurrence of coalescence in producing (warm) rain
	Relationship between drop shape and size distribution, radar reflectivity and rainfall rates
Cloud ice	Particle riming and the secondary production of ice particles
	Microphysics of hail production

RECOGNITION OF KEY UNCERTAINTIES IN WEATHER MODIFICATION

The current state of knowledge in weather modification as summarized in the preceding sections provides sufficient guidance to identify key uncertainties which need to be addressed before substantial progress in weather modification is likely to be made. Box 2.2 provides a list of key uncertainties which stem from the current state of knowledge in weather modification. These uncertainties transmute into questions which identify roadblocks where research should be focused and which constitute a framework that—with the concerted application of current technology, modeling, and statistical analysis described in the following chapter and Appendix B—can promise substantial progress in determining and demonstrating to what extent we influence, modify, or even control the weather. Such a framework clearly identifies critical roadblocks to progress where research resources should be focused.

BOX 2.2
Summary of Key Uncertainties

The statements in boldface type are considered to have the highest priority.

Cloud and precipitation microphysics issues

- **Background concentration, sizes, and chemical composition of aerosols that participate in cloud processes**
- Nucleation processes as they relate to chemical composition, sizes, and concentrations of hygroscopic aerosol particles
- Ice nucleation (primary and secondary)
- Evolution of the droplet spectra in clouds and processes that contribute to spectra broadening and the onset of coalescence
- Relative importance of drizzle in precipitation processes

Cloud dynamics issues

- **Cloud-to-cloud and mesoscale interactions as they relate to updraft and downdraft structures and cloud evolution and lifetimes**
- Cloud and sub-cloud dynamical interactions as they relate to precipitation amounts and the size spectrum of hydrometeors
- Microphysical, thermodynamical, and dynamical interactions within clouds

Cloud-modeling issues

- **Combination of the best cloud models with advanced observing systems in carefully designed field tests and experiments**
- Extension of existing and development of new cloud-resolving models explicitly applied to weather modification
- Application of short-term predictive models including precipitation forecasts and data assimilation and adjoint methodology in treated and untreated situations
- Evaluation of predictive models for severe weather events and establishment of current predictive capabilities including probabilistic forecasts

- Advancement of the capabilities in cloud models to simulate dispersion trajectories of seeding material
- Use of cloud models to examine effects of cloud seeding outside of seeded areas
- Combination of cloud models with statistical analysis to establish seeding effects

Seeding issues

- **Targeting of seeding agents, diffusion and transport of seeding material, and spread of seeding effects throughout the cloud volume**
- **Measurement capabilities and limitations of cell-tracking software, radar, and technologies to observe seeding effects**
- Analysis of recent observations with new instruments of high concentrations of ice crystal
- Interactions between different hydrometeors in clouds and how to best model them
- Modeling and prediction of treated and untreated conditions for simulation
- Mechanisms of transferring the storm-scale effect into an area-wide precipitation effect and tracking possible downwind changes at the single cell, cloud cluster, and floating target scales

3

Evaluation Requirements for Weather Modification

Over the years the overriding critical issue for nearly all weather modification research and operational activities has been the need for evaluation and validation of the results. This Committee agrees with the views stated in many earlier assessments that objectivity, repeatability, and predictability are primary requirements in weather modification research, as well as independent confirmation with strong physical and statistical evidence. In recent years there has been some improvement in the evaluation and validation of cloud-seeding activities (e.g., more emphasis on randomization and double-blind studies), but these evaluation efforts have not been sufficient to make a clear case for supporting standard methodologies or for achieving predictable results. The challenge for the scientific community is to develop acceptable evaluation criteria to ensure that future research and operational programs build a solid scientific foundation for further advances. This chapter examines issues related to designing and evaluating weather modification experiments and commercial seeding operations.

PHYSICAL EVALUATION

The interpretation of observations in the light of established theory and the development of new theory based on laboratory experiments and observations in the atmosphere are sometimes called physical evaluation. A complete physical-dynamical numerical model of a cloud system (with and without seeding) would be the ideal version of a physical evaluation. If meteorologists had the skill to make perfect forecasts, they could estimate seeding effects by simply comparing test results with predictions. But such forecasting skills would require a complete physical-dynamical model of the relevant cloud systems, as well as a measurement system capable of establishing initial conditions for the model. Neither of these exists nor are they likely to exist in the foreseeable future. In considering the role of weather modification in the field of atmospheric science, it is important to emphasize that many of the uncertainties limiting an understanding of the physics and dynamics of seeded clouds are the same as those that limit quantitative precipitation forecasting in weather forecast models and cloud parameterizations in climate models.

An example of a physical evaluation can be found in early weather modification experiments that involved dropping dry-ice pellets into stratus clouds and observing the transition of supercooled drops into masses of ice crystals in the time and location predicted by laboratory studies and theory. Because the stratus was uniform over large areas and stable over long time periods (relative to the time required for conducting the experiment), and because the result could be replicated as often as desired, there was no need for elaborate statistical studies to establish a cause-and-effect relationship between the seeding and the subsequent development of ice crystals.

This example, however, is deceptively simple. Most cloud-seeding experiments have not resulted in responses as clear cut and repeatable as that of dry-ice seeding of supercooled stratus. Often the cloud systems of interest are highly variable in space and time and this variability is poorly quantified. Convective cloud regions suitable for seeding have unknown lifetimes and may be interspersed with regions where seeding would be ineffective. Thus far we are unable to trace the physical effects from the point of seeding to the end product of rain on the ground. Even our ability to measure the amount of rain reaching the surface leaves much to be desired, although recent advances in radar technology (described in Chapter 4) should lead to better measurement of rainfall. Due to such limitations, cloud scientists have had no alternative but to turn to statistical evaluations in their efforts to verify seeding effects.

STATISTICAL EVALUATION

To have reasonable confidence in the results of seeding experiments they must be carefully designed, conducted, and analyzed with the best techniques available. The goal is to minimize uncertainties resulting from the large variability in natural weather systems, from our incomplete knowledge of the physical processes involved, from our limited ability to measure the relevant meteorological variables and to target seeding agents, and from our inability to replicate experiments (in the strictest sense of the word).

Assessments of seeding effects most often consist of comparisons of the amount of precipitation (e.g., rain) measured in a target area with that from a control area. Many of these comparisons, especially in the early days of seeding, did not involve randomization. The target and control areas often were the same fixed geographical area, and comparisons were between measurements made during the seeding period and those from a period without seeding. Alternatively, the control area might be a geographically fixed area adjacent to (and meteorologically similar to) the target area. In this case, comparisons are made between measurements from the two areas during the same time periods. In either of these designs the comparisons are usually discounted because there is no way to allow for biases arising from temporal or spatial trends that may have been present during the trial period. A more statistically robust design, known as a cross-over, uses two similar fixed areas. During each test case one area is selected for treatment through a random process while the other serves as the control.

It has long been recognized that experimental proof of cause-and-effect relationships (as opposed to chance occurrence) requires randomization and replication (Fisher, 1958), especially when the test pool is highly variable as in the case of weather systems. A number of randomized seeding experiments have been designed and conducted with the aim of confirming a particular seeding effect. These experiments have provided a large fraction of our scientific data on clouds and storms, but most did not provide evidence sufficient to reject the null hypothesis of no seeding effect. A conclusion commonly reached in these experiments was that "there were indications of seeding effects based on physical measurements, but the data were not sufficient to reach statistical conclusions." Generally the suggested physical evidence for seeding effects was deduced from after-the-fact examination of the data. From the many kinds of measurements obtained certain ones may be selected because they appear to be associated with a useful seeding effect, perhaps in a particular partition of the data. The scientist then postulates a mechanism whereby the supposed effect might be linked to the treatment. Regrettably those postulates have not been verified by further experimentation.

Statisticians working with meteorologists have developed a range of design and analysis techniques for assessing seeding experiments. In addition to randomization and replication, a well-designed weather modification experiment may include pre-screening or blocking to reduce the variance in the test group, use of covariates, alternating target and control areas (cross-over design), and re-randomization as a means of coping with internal variance and small sample sizes. Classical hypothesis testing often is replaced by a comprehensive data analysis in which all of the measured variables are brought to bear on the question of seeding effects (Gabriel, 1979; Flueck, 1971). Another relatively new statistical method that may provide even better evaluation capabilities is the Bayesian technique, which can explicitly account for sources of uncertainty and complicated spatial and temporal dependencies (Appendix B). This technique could have major impacts on weather modification research if utilized.

Because of the significant natural variability in cloud systems, seeding experiments must acquire large numbers of experimental units if a relatively small seeding effect is to be distinguished from chance variations. This has meant long and expensive experiments. Protracted experiments are more vulnerable to secular changes in environmental factors (e.g., weather, land use, background aerosols), many of which can be handled by proper randomization (at least in principle). For instance, it would have taken over 50 years to carry out a full statistical evaluation of the effects of seeding on hurricanes using 1970s technology (Simpson et al., 2002).

The ACWC introduced the concept of exploratory and confirmatory experiments to differentiate between searching for possible seeding effects and formal testing of a postulated effect. Statistics can be used in an exploratory manner to guide understanding of the important physical processes in a conceptual model. For instance, in recent hygroscopic seeding experiments (i.e., the South African, Mexican, and Thailand experiments described in Appendix A) statistical analyses indicated increases in rainfall, but they appeared later in time than anticipated and did not conform to the original hypothesis. Dynamical effects, which were not included in the original hypotheses, were invoked to explain the results. The statistical analyses thus led to the development of new hypotheses to explain the experimental results.

Some may argue that a single test variable is necessary to guard against multiplicity and to provide an unambiguous proof of concept. However, data from cloud-seeding experiments are highly variable, and this reduces the power of a single test to detect differences. To fully consider and evaluate the myriad of variables in weather modification experiments, multivariate statistical process models that exhibit spatial and temporal dependence are much better suited (Appendix B).

Statistics can be used not only as a tool to test proof of concept, but also as a tool for discovery (a mathematical “magnifying glass”). The advances in statistical sciences described in Appendix B have not yet been fully applied in weather modification research. Application of these methods, together with the advances in measurement technology and modeling, promises improvements both in verification and in our physical understanding of the processes involved. Appendix B provides an in-depth scientific discussion of the current methods available in statistical science with direct application to weather modification. In the sections that follow a more general discussion of evaluation requirements in weather modification is presented.

MEASUREMENT UNCERTAINTIES

Even though the classical methodologies of testing cloud seeding are well established, several kinds of difficulties are encountered in practice. The objective of assessing the results of a cloud-seeding experiment is to establish whether the test variate, such as the total rain in a target area under treatment, is different than it would have been with no treatment. Obviously, one must then be able to measure the test variate with sufficient accuracy to separate the effects of treatment from natural variability. This has been a major problem in cloud-seeding experimentation.

For instance, experiments aimed at increasing rainfall typically have used networks of surface-rain gauges as their measurement system. Rain gauges give a fairly accurate measurement of rain at the point of the gauge, but rain is highly variable in space and time, especially in convective weather situations. The frequency distribution of storm rainfall amounts is highly skewed, with a large number of small events interspersed with a small number of large events that account for most of the total rain. With the density of rain gauges normally attainable, and integration over periods of hours, area-average rain amounts have large errors, especially in convective situations. Radar is being used more frequently for measuring rain, with the advantage of much better spatial coverage and temporal resolution. But this introduces another variable, namely, the relation between the measured radar parameter and rainfall at the surface, which depends on the drop-size distribution, which may be affected by seeding. Other direct and indirect measures that have been used for assessing seeding trials, such as hail-fall energy and crop damage estimates, also introduce additional layers of variability that must be accounted for.

UNCERTAINTIES IN DEFINING AND TRACKING THE TARGET

In many cloud-seeding experiments the experimental units are elusive, hard to define, and difficult to follow in time. In fact, to see a convective cloud as a single entity is an illusion. Clouds are transitory, always evolving and mixing internally and with their environment. These basic properties of clouds make it difficult to keep track of seeded units and to replicate the treatment in successive trials. At the same time, however, this inherent mixing within the atmosphere plays an essential role in most seeding experiments. In the immediate vicinity of the release point from seeding devices the concentration of seeding materials is much too high for effective cloud treatment. Operators depend on atmospheric mixing to dilute the seeding material before it reaches the target area. Further mixing then reduces the concentration of seeding materials and may reduce it to the level where it becomes ineffective.

No two clouds are identical, and clouds are not independent of one another. A limited number of experiments have found that tracer materials released into the sub-cloud updraft of a developing convective cloud were subsequently found in the rain coming from neighboring clouds, thus suggesting some degree of interaction. The amount of cloud interaction probably decreases with separation in space and time. The degree of dependence between different clouds on the same day, or clouds in the same area and air mass on different days, is not measurable and thus hard to allow for in assessing seeding trials. This issue is often simply ignored in many seeding studies. However, recent advances in this area integrating several observational tools could help to address these issues (Mueller et al., 2003).

A variety of tracking methods and software packages are used to evaluate the results of seeding activities. For example, the South African and Mexican hygroscopic seeding experiments (WMO, 2000) used the storms-based Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN) tracking software to evaluate their radar-based results. the hygroscopic seeding experiments in Thailand (Silverman and Sukarnjanaset, 2000) used a variable-radius floating target that moved with the mean radar echo motion. The recent glaciogenic experiments in Texas (Rosenfeld and Woodley, 1993) and Thailand (Woodley et al, 2003) used a hierarchy of radar-tracked cells imbedded in fixed-radius floating targets that are moved with the mean-cell motion.

UNCERTAINTIES IN REACHING THE TARGET

When ice-forming agents are released directly into the top of a supercooled stratus cloud, there is little question whether it reaches a susceptible region of cloud. When the seeding agent is released directly into the updraft under a convective cloud it will become part of the updraft and presumably will be carried to a level where it can be effective.

In the case of area-wide sub-cloud seeding and orographic seeding, the agent usually is released upwind of the target. Whether it reaches the intended target, and if so in what amounts will depend on the winds and turbulence between the release point and the target. In some contexts the means for measuring and forecasting these winds in real-time is very limited and thus is another source of uncertainty. Some seeding particles from ground-based generators could be scavenged by snow and ice and therefore diminish the effects of seeding (Warburton et al., 1995). For all of these reasons the targeting and mixing of the seeding material through a cloud remains highly uncertain. However, with new high-resolution mesoscale numerical models and remote sensors, new opportunities exist to address these issues, especially in winter orographic situations. In-cloud and cloud-top seeding introduces similar uncertainties but could potentially be addressed with new modeling and observational tools. As discussed in Chapter 4 the use of chaff fibers or gaseous tracers may be a particularly good strategy for tracking the dispersal of seeding material and the resulting cloud effects.

ASSESSING THE AREA AFFECTED

The areas affected by cloud seeding remain an open question. In after-the-fact analyses several rain enhancement projects have reported evidence for physical effects outside the area or timing originally designated as the target, or beyond the time interval when seeding effects were anticipated. For example, in recent large particle hygroscopic seeding trials involving warm-base convective clouds in Thailand and Texas, increases in rain were reported 3 to 12 hours after seeding was conducted, well beyond the time at which direct effects of seeding were expected and possibly outside the target area. In Project Whitetop the seeding appears to have decreased rain in the area immediately downwind of the seeding release line. This was followed by apparent rainfall increases well downwind in space and time. Does this mean that the scientists misjudged where seeding materials were actually reaching receptive cloud conditions or does it mean that the primary effects of seeding were followed by secondary effects well beyond the original target? Such secondary effects could occur, for instance, if seeding materials become entrained in a downdraft and then are carried outward into the updraft of other clouds. In the case of the hygroscopic seeding experiments the postulated dynamic effects due to microphysical and dynamical interactions in the cloud and sub-cloud region and with the environment could result in longer-lived or progeny clouds. Another related uncertainty in seeding convective systems is whether a positive effect on some individual clouds (or cloud complexes) will aggregate to result in increased area rainfall.

An associated question addressed in Appendix A and Box 1.1 is that of “robbing Peter to pay Paul.” Debates about the effects of seeding beyond the target area point to the fact that weather modification can be viewed as more than just a means to increase local precipitation. Rather, it can be viewed as a means to alter natural hydrological cycles by increasing the number of times that atmospheric water is recycled at the Earth’s surface. As more is learned about the global water balance and as new tools enable the cloud scientist to better understand clouds and their response to seeding, the question of extended area affects likely will become better defined and understood.

4

Tools and Techniques for Advancing Our Understanding

The past few decades have seen the development of a multitude of new tools for measuring and modeling physical processes of cloud and storm systems. It is becoming feasible to carry out detailed studies of the chain of physical events in the evolution of a cloud system. This will lead to more definitive assessments of the effects of seeding, refinements of physical hypotheses, and “prospecting” information about suitable seeding targets. This chapter identifies important developments in observational technologies and modeling and data assimilation capabilities and discusses how these new tools and techniques can best be applied to studies of enhancing atmospheric water resources and mitigating hazardous weather.

MEASUREMENT AND OBSERVING TECHNOLOGIES

Several large weather modification research programs were carried out in the late 1960s and early 1970s, including the National Hail Research Experiment aimed at hail suppression, the Sierra Cooperative Pilot Project aimed at snowpack enhancement, and the High Plains Experiment aimed at warm-season rainfall enhancement (among others discussed in Chapter 2 and Appendix A). These experiments contributed to the development of many new observational instruments and facilities such as the Wyoming King Air research aircraft, the NCAR CP-2 dual-wavelength radar, the CHILL dual-wavelength and Doppler radar systems, NCAR and NOAA Doppler radars, and the NCAR Portable Automated Mesonetwork. These systems defined the state of the art at the time and contributed much to our current understanding of precipitation processes.

Although weather modification research has declined since that time, observing technologies with which the field could benefit have continued to advance. Cloud-seeding research activities can now employ revealing measurements that were unavailable in earlier decades, particularly in terms of remote sensing. The new observations offer more accurate and higher resolution precipitation measurements and three-dimensional depictions of the structure, airflow, and hydrometeor composition of clouds before and after seeding.

Several remote-sensing advances of great potential value to cloud seeding were fostered by urgent needs in other fields, including requirements for improved severe storm warnings, detection of aircraft icing conditions, and better understanding of the role of clouds in climate change. Some of these new observing technologies have had cursory initial demonstration uses in actual weather modification experiments, but none have as yet been used as integral components of experiments designed to test and evaluate specific scientific hypotheses. Thanks to continuing development in other fields these technologies are reaching a level of maturity that makes their wider use in cloud-seeding research and operations feasible and attractive. The following observational tools are likely to provide contributions to future weather modification studies.

Doppler Radars

At the time of the major weather modification field studies mentioned earlier, the use of Doppler radar was embryonic, the performance characteristics of Doppler radars were still topics of research, and multiple Doppler networks were just emerging. In the subsequent decades attendant research led to operational deployment of Doppler radars for precipitation measurement, severe weather detection and warning (the Next Generation Radar, or NEXRAD, network), and for detection and warning of hazardous wind shear at airports. Serafin and Wilson (2000) describe the status of these operational systems. These radars produce data that are of research quality and the data are becoming available in real time (for instance, through the Collaborative Radar Acquisition Field Test [CRAFT]).

Another major airborne instrument development has been the advent of airborne Doppler radars flown on NCAR and NOAA research aircraft as well as on the NASA ER-2. These radars have produced information of unprecedented accuracy and resolution in precipitating systems, leading to improved understanding of the structure of and air motion fields in hurricanes (Heymsfield et al., 2001), severe storms, and even in optically clear air (Wakimoto and Liu, 1998). New understanding of the genesis and evolution of tornadoes and the intensity of hurricanes has been gained from these observations. Highly mobile ground-based radars have also demonstrated their utility for high-resolution measurements in the challenging conditions prevalent in severe storm environments (Wurman and Gill, 2000).

Atmospheric Profiling

Much progress has been made in the arena of atmospheric profiling, and sensitive wind profilers now are available commercially. These devices measure profiles of tropospheric winds continuously and when coupled with acoustic sounders, also measure profiles of temperature (May et al., 1990). Ground-based GPS receivers can routinely measure path-integrated water vapor. Progress has also been made in optical sensing of the atmosphere. Differential absorption and Raman-scattering lidar are capable of measuring water vapor profiles (Ismail and Browell, 1994; Melfi and Whiteman, 1985). Solid-state and reliable Doppler lidars have been used very effectively for measurements of winds and turbulence (Poon and Wagoner, 1995). Scientists have recognized the importance of better water vapor measurement techniques and completed the most comprehensive research project ever attempted to better characterize the three-dimensional structure of water vapor (described at <http://www.atd.ucar.edu/dir_off/projects/2002/IHOP.html>). Research interests in profiling the atmosphere have become so active that a special issue of the *Journal of Atmospheric and Oceanic Technology* has been devoted to the topic (JAOT, 2002).

Microwave Radiometry

In glaciogenic seeding the objective is to use a seeding agent (nuclei or dry ice) to convert tiny supercooled water droplets to ice crystals, which grow rapidly and precipitate out of the cloud. Thus, locating regions of high concentrations of supercooled liquid in natural clouds is of paramount importance. A promising tool for this "prospecting" work is the dual-channel microwave radiometer, which retrieves the path-integrated total amount of liquid water and water vapor along its beam by simultaneously measuring emissions from vapor and liquid at frequencies near 21 GHz or 23 GHz and 31 GHz (Westwater, 1993). Ground-based, unattended vertically pointing microwave radiometers have been used for monitoring aircraft icing conditions aloft and in atmospheric radiation climate research programs. These units, based on technology developed in the 1980s, are now commercially available, as are newer ones that monitor additional frequencies to provide coarse vertical profiles of cloud liquid water content and temperature. The ability of a scanning microwave radiometer to observe cloud-seeding opportunities was demonstrated by the NOAA/ETL in the Sierra Cooperative Pilot Project orographic snowpack enhancement experiment (Snider and Rottner, 1982). Aircraft-mounted microwave radiometers are also now available and may be suitable for cloud-seeding activities.

Polarimetric Radar

Polarization-diversity (dual-polarization) radars measure signals backscattered from targets in two orthogonal orientations to discriminate between water and ice in clouds, detect hail, identify the types of particles present (see Plate 6), and attain more accurate estimates of rainfall rates using differential phase (K_{DP}) methods (Bringi and Chandrasekar, 2001). These capabilities are of great potential value in assessing cloud-seeding experiments. For individual cloud studies, polarimetric particle classifications have the potential to reveal the transformation of supercooled liquid water droplets to ice crystals in glaciogenic seeding and the development of large drops in hygroscopic seeding. They can also follow the movement and dispersion of seeding aerosols using microwave chaff fibers as tracers (as discussed later). Three-dimensional depictions of these processes may be observed as they occur using ground-based or airborne polarimetric radars. The particle classifications also can refine conventional reflectivity-based rainfall estimates by identifying regions of echo that are not rain or contain rain with contaminations of hail, snow, ground clutter, or insects. The new differential phase estimation of rainfall rate offers a method for measuring the ground-level result of seeding that is free from several factors that have historically degraded the simple reflectivity-based estimates of precipitation. The method avoids or minimizes problems related to hardware calibration errors, attenuation, partial beam filling, partial beam blockage, the presence of hail, and variability of drop size distributions (Zrnic and Ryzhkov, 1996).

Polarization-diverse radars are available only in the research community, but their numbers are expanding. Most dual-polarization research in the United States has been conducted with the large S-band (3 GHz) weather surveillance radars, such as those at NCAR, NOAA's National Severe Storms Laboratory, and Colorado State University. NOAA's Environmental Technology Laboratory uses polarimetric methods with much smaller millimeter-wave radars (35 GHz) for cloud hydrometeor identifications and at X band (9 GHz) for chaff tracer tracking and differential-phase rainfall estimations. Even smaller, highly mobile polarization-diversity millimeter-wave radars are operated on trucks by the University of Massachusetts and on research aircraft by the University of Wyoming. The technology now exists to inexpensively upgrade radars to multiparameter capability; and the national network of operational S-band weather surveillance radars (WSR-88D or NEXRAD) may be upgraded to include polarimetric capabilities by the end of this decade, depending in part on results of the Joint Polarization Experiment demonstration in Oklahoma in 2002–2003 (NRC, 2002).

Millimeter-Wave Cloud Radar

Millimeter-wave cloud radars use wavelengths of 8 mm or 3 mm that are more than an order of magnitude shorter than those of S-band weather surveillance radars. Lhermitte (1987, 1988) pioneered the use of 3 mm wavelength for sensitive and high-resolution observations of developing clouds and precipitation. Use of this short wavelength offers unique opportunities for both airborne research (Leon and Vali, 1998; Pazmany et al., 1994) and ground-based studies (Martner et al., 2002).

The primary attributes of these radars are superb sensitivity and resolution (<50 m), which enable them to detect very weak targets, such as non-precipitating clouds, with remarkable detail and without the need for large antennas and powerful transmitters. The small size and weight of their hardware components makes mobility highly feasible. Trailer-mounted, truck-mounted, and airborne versions are now in operation and the first space-borne cloud radar (CloudSat) will be launched in about 2005. The main disadvantages of millimeter-wave radar are severe attenuation by liquid water clouds and rain and limited range coverage. Thus, cloud radars are best suited for short-range observations of the fine-scale structure of clouds, snowstorms, and weak rainfall.

These radars can possess all the scanning, Doppler, and polarization-diversity capabilities that have been developed originally for the much larger microwave radars. A decade of research at NOAA/ETL on polarimetric identification of cloud hydrometeors with millimeter-wave radar (for the purpose of remote detection of aircraft icing) has derived hydrometeor polarimetric signatures (Figure 4.1) that have obvious applications to cloud-seeding experiments (e.g., Reinking et al., 2002). Short-wavelength cloud radars, especially airborne units, hold great promise for revealing the physical transformations in the seeded regions of clouds. Longer wavelength radars, however, are

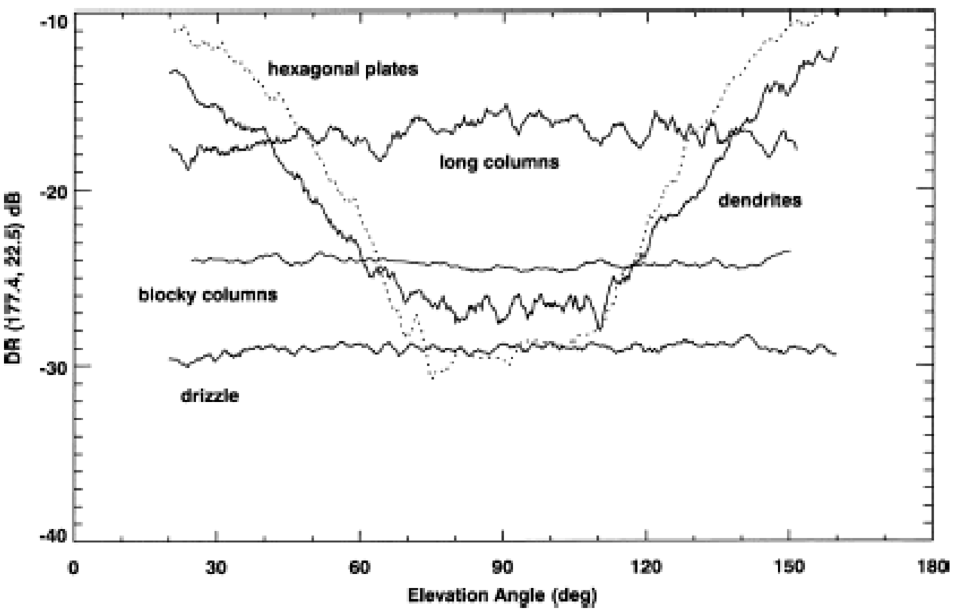

FIGURE 4.1 Depolarization ratio as a function of antenna elevation angle, showing signatures of various hydrometeor types obtained with scanning millimeter-wave cloud radar. Each signature type has been matched to theoretical model simulations and verified with in situ particle sampling. SOURCE: Reinking et al. (2000).

likely to remain the primary tool for observing and assessing the ultimate desired result of seeding in terms of precipitation reaching the ground.

Combining simultaneous cloud radar and radiometer observations of clouds overhead to retrieve estimated profiles of hydrometeor mass content, median size, and concentration has become a routine procedure at the U.S. DOE CART sites and in other cloud/climate research experiments. Millimeter-wave radar data are combined with microwave radiometer data for retrievals in liquid clouds, such as stratus (Frisch et al., 1995), and with infrared radiometer data for retrievals in optically thin ice clouds, such as cirrus (Matrosov et al., 1992). Retrievals of properties in mixed-phase clouds are more problematic. These kinds of active/passive remote sensing combinations could benefit cloud-seeding research, particularly if the theory and technology can be extended to scanning applications.

Perhaps the most impressive demonstration of the combined use of cloud radar and microwave radiometers in a cloud-seeding experiment is the case described by Reinking et al. (2000). Earlier numerical modeling simulations by Bruintjes et al. (1994) indicated that under certain wintertime stability and airflow conditions, the mountains of central Arizona initiate the development of a strong gravity wave, which produces sustained updrafts that condense vapor into significant amounts of supercooled liquid water. This orographically induced standing wave of supercooled liquid represents an attractive target for glaciogenic seeding to increase snowpack on the downwind Mogollon Rim, which is the state's major water supply source. A field program incorporating ground-based remote sensors and aircraft observations was established in 1995 to investigate the model predictions. Plate 7 shows a prominent wave across the Verde Valley as observed by a scanning cloud radar and strong accentuation of liquid water content in the ascending part of the wave measured by a steerable microwave radiometer, thereby confirming the model prediction.

GPS and Radar Cell Tracking Software

In recent years cloud-seeding operations have relied heavily on sophisticated real-time displays of the radar reflectivity of storms and the location of seeding aircraft to manage and assess seeding operations. Although there are many cell-tracking programs, such as the one described by Rosenfeld (1987), the TITAN software package developed at NCAR is most used among these systems (Dixon and Wiener, 1993). This software objectively identifies discrete storm cells, follows their movement and development, and keeps statistics (Plate 8). In addition to providing guidance for real-time operations, TITAN is used extensively in subsequent analysis to examine the effects of seeding, in terms of reflectivity enhancements, on treated storm clouds. It has become an important tool in many operational convective cloud-seeding operations and represents a valuable aid for automating the display and analysis of radar data. TITAN has evolved since 1993 and has several features that are specifically aimed at weather modification applications. Among these are the ability to distinguish independent cells within merged cells, and the use of an altitude threshold that mitigates the effects of the Earth's curvature. In weather modification research an annulus between 15 km and 90 km is usually used as the region in which echoes are reliably tracked.

For TITAN to be effective, accurate location of seeding and research aircraft is essential. This was a significant impediment to many weather modification studies in the past. The advent of the GPS now provides a superb and inexpensive tool for this purpose (Plate 7). In addition ground-based GPS receivers, in combination with other co-located routine temperature and pressure measurements, are now available as a national network (Ware et al., 2000) for measurements of column-integrated water vapor, a necessary measurement in weather modification research. Dense networks of such measurements could be cost-effectively deployed in future experiments. Finally, GPS tracking is now used with radiosondes to provide very high-resolution vertical profiles of temperature, humidity, and winds (Hock and Franklin, 1999; Aberson and Franklin, 1999).

Satellite Imagery

Satellite-borne instrumentation provides horizontally contiguous observations of water vapor fields, aerosol amounts and particle sizes, cloud-top temperature, particle size and thermodynamic phase, and to a limited extent in-cloud processes and precipitation over a large aerial extent. For instance, the Tropical Rainfall Measuring Mission (TRMM) includes precipitation radar, a microwave imager, and a visible-infrared radiometer, all of which will help improve modeling and prediction of rainfall processes. CloudSat, an upcoming multisatellite, multisensor mission, will utilize a millimeter-wave radar to profile the vertical structure of clouds, and measure the profiles of cloud optical properties, cloud liquid water, and ice-water content. These data can be used to evaluate and improve the way clouds are parameterized in models. The Global Precipitation Measurement (GPM) Microwave Imager will utilize a series of passive microwave radiometers to provide near-global measurements of precipitation.

These capabilities have opened a new era in cloud physics and could provide many new opportunities for assessing the effects of weather modification. Satellite observations already are playing an important role in studies of inadvertent weather modification by tracking plumes of industrial pollution and their effects on precipitation suppression, as well as hygroscopic effects of salt aerosols that aid in restoring precipitation. Rosenfeld and Lensky (1998) developed a new methodology for using TRMM and the Advanced Very High Resolution Radiometer sensors to infer the microstructure of convective clouds and their precipitation-forming processes with height.

In Situ Measurements

Robert Knollenberg pioneered the development of laser based measurements of the particle size distributions in clouds. These revolutionary devices, usually mounted on the tips of research aircraft wings, use laser light to image and count particles. Knollenberg probes rapidly became the tools of choice for cloud physics researchers. These Particle Measuring Systems, Inc. (PMS) probes (Knollenberg, 1981) together with hot-wire liquid water probes (King, 1978) have been the principal instruments for characterizing aerosol and cloud particle properties for the past two decades. They are useful for understanding the types and numbers of hydrometeors and their evolution. They have also been used to develop interpretative algorithms for ground-based radar measurements. In many weather modification experiments the probes have been deployed to observe the hydrometeor evolution that takes place before and after seeding.

Through the years new probe designs have evolved, and they now cover a wide range of particle sizes. Some designs use forward scattering to detect very small particles, including aerosols. At present, however, no single instrument can provide simultaneous, accurate information about cloud particle spectra and liquid water content. A combination of instruments is needed, and this situation seems unlikely to change in the near future.

The Passive Cavity Aerosol Probe measures the size distribution of aerosol particles between 0.1 μm and 3 μm diameter in 15 size channels. The Forward Scattering Spectrometer Probe (FSSP-100) measures cloud droplet distributions between 0.5 μm and 47 μm diameter in 15 size bins. Another version of this probe (FSSP-300) with higher size resolution for aerosol and cloud droplet sizes between 0.3 μm and 20 μm diameter has also been used extensively. The Fast-FSSP (Brenguier et al., 1998), an improved version of the FSSP-100, provides better sizing of the droplets and more accurate determination of the concentration of particles.

Several optical array probes have been developed to measure the concentration and sizes of larger particles. The technology in use currently is the Optical Array Probe (OAP-260X) which measures the concentrations and sizes of particles between 40 μm and 640 μm diameter. Optical array probes have also been developed to provide two-dimensional images of hydrometeors, with a resolution of 25 μm for cloud particles and 300 μm for larger hydrometeors such as large ice crystals and raindrops.

The Cloud, Aerosol and Precipitation Spectrometer (CAPS) (Baumgardner et al., 2000) instrument consists of five sensors: the aerosol and cloud droplet spectrometer (CAS) (0.35 μm – 50 μm diameter), the cloud imaging probe (CIP) (25 μm–1550 μm diameter), the liquid water detector (0.01 gm^{-3}–3 gm^{-3}), the air speed sensor, and a temperature probe. The CAS measures the conventional forward-scattering light from single particles but also the back-scattered light that provides an estimation of the aerosol refractive index. In addition, the sample volume is defined similar to that used in the FSSP-300X (Baumgardner et al., 1992). These improvements provide an extended size range of particle measurement that covers much of the accumulation mode aerosols and up to small drizzle drops in clouds. Due to the improved electronics many of the limitations associated with the FSSP-100 have been overcome. The principal improvements of the CIP are added stability against vibration, decreased response time, and decreased dead time that provides for better resolution, sizing, and more accurate particle concentrations. The liquid water content detector uses technique described by King (1978). Preliminary results using the CAPS have shown increased capability compared to the conventional PMS probes.

A new generation of particle spectrometers uses optical response rather than direct single-particle collection. The Gerber Particle Volume Monitor (Gerber et al., 1994) measures the liquid water content, drop surface area, and effective radius. The light scattered in the forward direction by an ensemble of drops is optically weighted and summed on a photodetector. The Cloud Droplet Spectrometer (CDS) (Lawson and Cormack, 1995) measures the forward-scattered light from an ensemble of drops. The CDS also computes drop size from the raw scattered light by inverting the measurements. The measurement has inherent advantages to overcome the limitations of single particle sizing and counting methods. Lawson et al. (1996) describe preliminary measurements with this instrument.

Another instrument, the Cloud Particle Imager (CPI) uses innovative new technology to record high-definition digital images of cloud particles and measure particle size, shape, and concentration (Lawson, 1997; Lawson and Jensen, 1998). The high quality of the CPI images supports the generation of individual size distributions for different types of particles (see Figure 4.2). Due to varying depth of field (depending on the size of the particles), the imaging sample volume of the CPI varies from about 0.002 cm^3 to 0.2 cm^3. A drop-off in particle detection efficiency starts at about 25 μm, thus the small end of narrow particle distributions (such as a typical distribution of cloud drops) will be undercounted. Research is ongoing to interpret the measurements from this instrument and its operational limitations. Korolev et al. (1999) described some recent measurements using this instrument.

Another important parameter is the measurement of LWC. While LWC can be calculated from the FSSP, the most widely used instruments have been the Johnson-Williams and CSIRO-King probes. The LWC is determined from the cooling effect of cloud droplets impinging on a heated sensor element that is exposed to the airflow

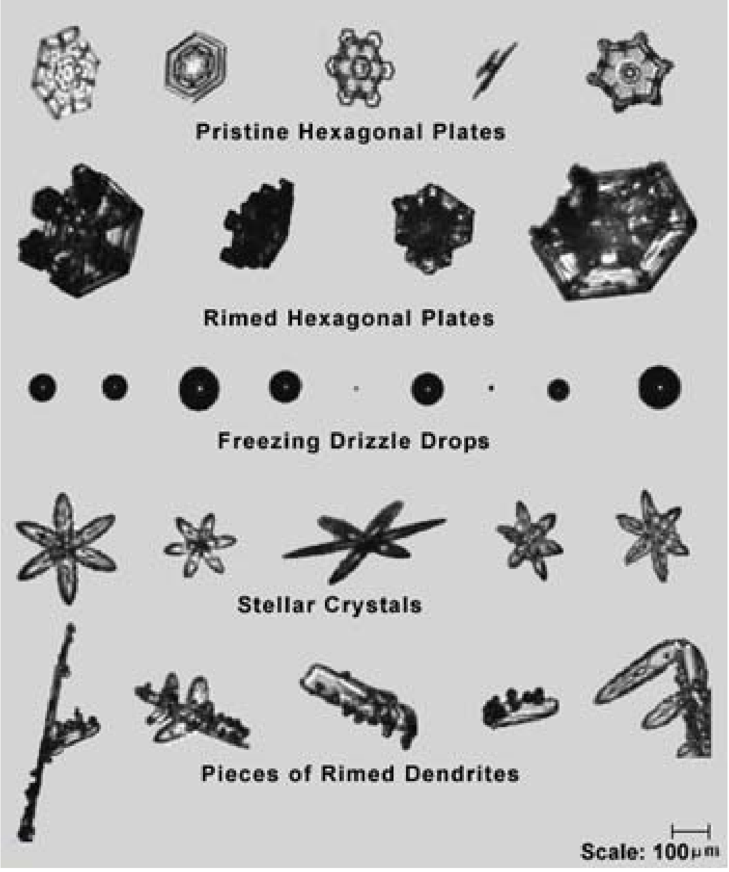

FIGURE 4.2 Particle images from the CPI instrument SOURCE: Lawson et al. (1998).

outside the aircraft. Limitations exist for all instruments measuring LWC, but for the King probes, errors occur when droplet diameters become greater than 50 µm as droplets break up on the sensing element and are removed by the airflow before they evaporate completely; this causes an underestimation of liquid water. Large quantities of ice particles also are a limiting factor (Fleishauer et al., 2002). The Gerber and CDR probes are also used to measure LWC. A comparison of more than 20 different types of probes (Strapp et al., 2000) indicated that the Nevzorov total-water-content probe (Korolev et al., 1998) is the most accurate hot-wire estimate of LWC in water-only clouds with large droplets.

Tracers

A difficult problem that has plagued many cloud-seeding experiments and operations is the question of whether the seeding material actually reaches the targeted regions of cloud, and whether it arrives there in effective concentrations. This is especially true for ground-based seeding operations, but it also applies to seeding from aircraft. Tracer techniques offer valuable information on nucleant transport and dispersion. The tracer is released together with the seeding material, and its location and concentration is subsequently measured as a proxy for the nucleant.

The most widely used tracer for cloud seeding is SF_6, an inert, anthropogenically produced compound that can be detected in incredibly small concentrations (Stith and Benner, 1987) but requires *in situ* sampling, which can be difficult. Other *in situ* techniques include airborne ice-nuclei counters and chemical analysis of the silver content (i.e., seeding material) in snowfall.

A particularly promising remote-sensing tracer method uses radar to track microwave chaff, which consists of very thin aluminum-coated glass fibers cut to half the wavelength of the observing radar. Chaff fibers released with or without seeding material show by direct measurement the actual transport and dispersion occurring within clouds. The fibers can be detected by radar in extremely small concentrations. The depolarization of the radar signal (the depolarization ratio) caused by the chaff allows it to be isolated from the signal of cloud intensity (reflectivity) and to be effectively tracked (Martner et al., 1992; Reinking and Martner, 1996). The volume treated and the location of treatment effects thus can be identified and assessed in relation to the total cloud volume. The concentration of chaff fibers can be computed from the radar measurements to yield information about diffusion rates. Although the chaff fibers fall faster than silver iodide aerosols (i.e., the seeding material), they provide a good approximation of the aerosol movement for several minutes after a release. This allows a polarization-diversity radar to observe and provide three-dimensional depictions of seeding aerosol movement to a treated cloud, as shown in Figure 4.3. Chaff tagging offers additional opportunities to remotely sense microphysical changes between tags. For instance, using such tagging, ice particle production and enlargement by seeding has been followed from the source to snow on the ground (Klimowski et al., 1998; Reinking et al., 1999, 2000).

All of these tracer methods have had modest demonstrations in weather modification research experiments, such as the 1993 North Dakota Tracer Experiment, a summer convective cloud-seeding research experiment that emphasized the use of a variety of tracer methods (Stith et al., 1996). But none has yet gained widespread, routine usage. Nevertheless, tracers are likely to be an important part of future seeding research because they offer vital observations of both the seeding material delivery and the cloud response.

MODELING AND DATA ASSIMILATION

Numerical modeling should be a key component of weather modification research. Computational resources are now probably sufficient to allow realistic cloud-resolving simulations with short-term predictive value. A properly constructed simulation model is internally self-consistent, complete in spatial and temporal coverage, and suitable for comparison with datasets. Such a model also can be the basis for a data assimilation process, which allows incomplete observational data from various sensing systems to be used to initialize a model's predictions. To fulfill these needs the microphysical processes relevant to weather modification need to be carefully incorporated and tested in the models, a process that is well under way. The

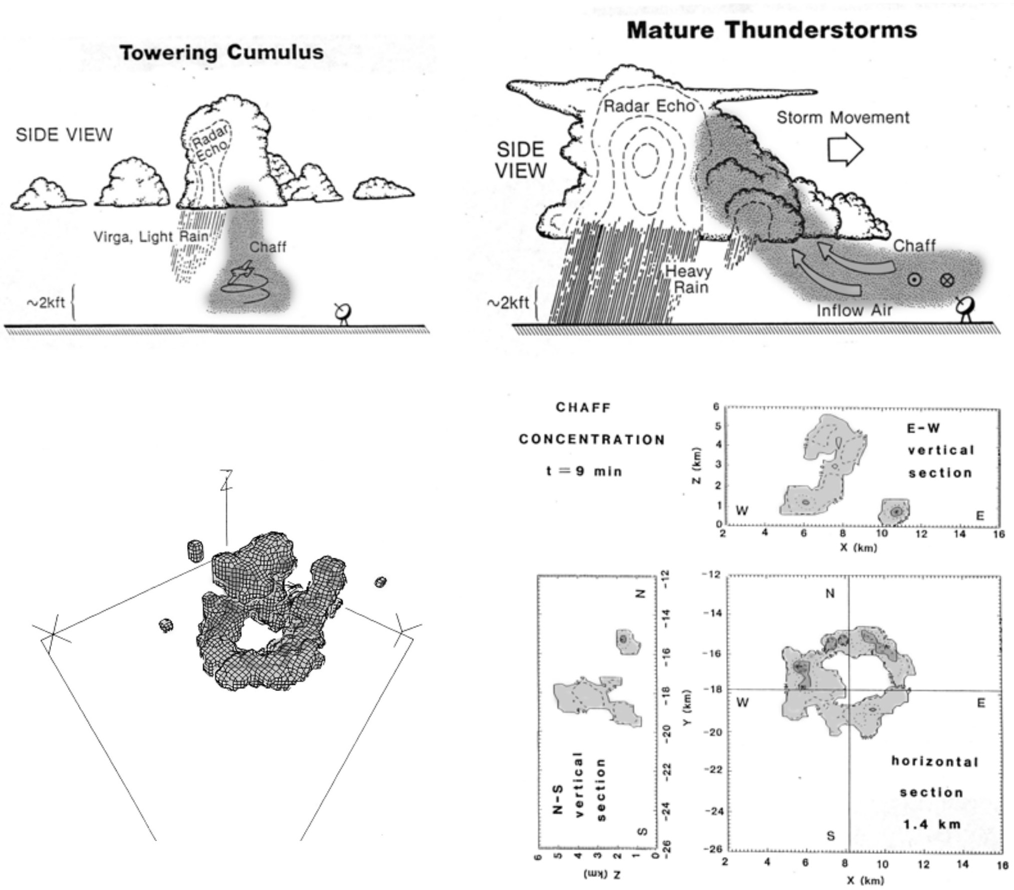

FIGURE 4.3 Radar observations of chaff released at the base of an isolated convective cloud in North Dakota. The top panels (a) illustrate the concept of releasing silver iodide seeding nuclei and chaff together and tracking their movement with polarimetric radar. Data from NOAA/ETL X-band radar shown in (b) depict the chaff-filled region of cloud 9 minutes after chaff was released by aircraft in a ring just below cloud base. By this time most of the chaff was still at cloud base, except for two rapidly rising turrets on the southwest side of the cloud. The cross sections in (c) show contour of chaff concentration at this time computed from the radar measurements. The chaff rose as high as 4.5 km from the release height within 13 minutes after the release, which is an average ascent rate of about 6 ms^{-1}. SOURCE: B. Martner, NOAA/ETL.

spatial distribution and nucleation properties of atmospheric aerosols are not well observed, but remotely observed cloud properties can be used to reduce some of the uncertainties. With adequate funding and encouragement further development of modeling relevant to weather modification could proceed. The Committee urges that such an effort be explicitly identified, including the support of field facilities that combine the most advanced observing systems with model development and application.

Cloud models with realistic simulations of seeding procedures and ice processes should be applied in three general modes: (1) planning and justification; (2) operations; and (3) post-operational analysis. They help to optimize cloud seeding procedures and to establish or refine physical hypotheses. They offer the only opportunity to see the effects of cloud seeding on identical (model) cloud situations, one seeded and one not seeded. They may be used to recreate cloud-seeding experiments from the past to help in the evaluation of those cloud-seeding effects. They can be used to simulate the dispersion trajectories of seeding material, provide real-time forecasting in support of field experiments and operations, examine the potential effects of cloud seeding outside of the seeded area, and aid in the statistical analysis of weather modification experiments.

The following sections review the history and methodology of modeling related to weather modification and evaluate future capabilities and needs. During the last 20 years cloud and storm modeling have been pursued most seriously for basic research and application to prediction and warning and to a lesser extent for application to weather modification. In an important review article Orville (1996) surveyed the progress of modeling related to weather modification to that date. A more recent review has been presented by Khain et al. (2000), and a substantial account of the NASA-Goddard modeling activities is given by Tao et al. (2003). The following account is based partly on these surveys.

Cloud Modeling History and Methodology

Cloud microphysics and dynamics have developed mostly from different academic bases. The discipline of cloud microphysics was developed mainly by physicists, while cloud dynamics tended to be a branch of fluid dynamics developed mostly by engineers, meteorologists, and oceanographers. A few scientists focusing on cloud processes have attempted the difficult task of combining these sources of knowledge. The theoretical bases of both dynamical and cloud microphysical processes have existed for some 30 to 40 years. Computing facilities and techniques, however, were much too limited to allow realistic model simulations until fairly recently. Early models of microphysical processes tended to be based on assumed particle trajectories, with almost no dynamic content, while early cloud dynamics models contained only the most limited microphysical parameterizations. As computing hardware and numerical technology evolved, the dynamical and microphysical simulations advanced and became mutually accessible.

An early but sometimes still used form of modeling is based on the plume theories for convection developed by fluid dynamicists in the 1940s and 1950s, first applied to prediction of nuclear bomb effects (Morton et al., 1956). A few one-dimensional equations are applied, representing the budgets of mass, buoyancy, moisture, and momentum in a cloud. These one-dimensional steady-state models are based on ordinary differential equations, and they have coupled microphysics and dynamics (Simpson et al., 1965; Simpson and Wiggert, 1969; Cotton, 1972). In the more modern versions a realistic environment may be assumed, with natural convection forced by condensation heating and freezing. Cylindrical or slab symmetry normally is required, which limits or neglects the effects of mean shear. Microphysical processes may be simulated, but neither the distribution of seeding agents nor the trajectories of precipitation particles can be realistically followed. A list of such models, designated as "one-dimensional steady state" or "one-dimensional time dependent" is given by Orville (1996).

The first non-steady numerical simulations of cloud convection date from the 1960s (Ogura, 1963; Orville, 1965) and were two dimensional, usually slab symmetric. Precipitation was introduced with varying levels of sophistication in the late 1960s, and attempts at thunderstorm simulation were made by Takeda (1971). The importance of the third dimension followed the clarification of the important differences between two- and three dimensional turbulence by Fjortoft (1953) and Kraichnan (1967). The first three dimensional simulations of boundary layer stratocumulus, cumulus, and deeper convection were presented in the mid-1970s. Those which produced the greatest impact, however, were the Klemp and Wilhelmson (1978) and subsequent simulations (see review by Klemp, 1987), which showed how shear could contribute to convective dynamics and produce thunderstorms with strong rotation and other observed "supercell" characteristics. "Bulk" microphysics were used, with just two categories of liquid water: cloud and rain. The transformation from cloud water to rainwater involved crudely simulated processes of autoconversion and collection.

Models aimed at more accurate simulation of microphysical processes (usually at the expense of dynamic reality) were also being developed. These included the Orville and Kopp (1977) hailstorm model and later the Orville and Chen (1982) simulations, oriented specifically to cloud seeding. In the latter the microphysical module—though still confined to "bulk" processes—contained four categories of cloud ice with fairly complex conversion algorithms, but the domains remained two dimensional. The correct simulation of the thermodynamic effects associated with precipitation processes—melting, evaporation, and recycling of ice and water particles into new cloud updrafts—is usually dependent on having three dimensions and fairly high resolution.

Since Orville's (1996) report, it has become possible to incorporate more detailed cloud physics algorithms into three-dimensional dynamics simulations. The original single moment bulk schemes were expanded to two moment schemes (Meyers et al., 1997), allowing more freedom for the distributions of hydrometeors to respond to physical processes. A method used frequently now is to define the mass distribution of particles by bins covering size ranges, with each bin larger by some factor than the previous one. The particles in each bin are allowed to grow or shrink by condensation, evaporation, deposition, and coalescence; to freeze or melt; to settle gravitationally; and to shed water or break up into smaller drops. Thus, the number of particles in each bin may increase or decrease with time. This method obviously requires greater computer memory and speed than for the bulk process assumptions. These simulations were first done in a zero-dimensional mode that follows a supposedly uniform parcel up or down (Berry and Reinhardt, 1974). Later the models were pursued in two or three dimensions in the context of cumulus clouds (Kogan, 1991) or shallow cloud-topped mixed layers (Kogan et al., 1995), for which the microphysics consists of purely liquid water processes. More recently simulations have been carried out for deeper clouds with large drops, freezing processes, and simulated seeding with cryogenic or hygroscopic agents (Khain et al., 2000, 2001; Khain and Sednev, 1995, 1996; Reisin et al., 1996a,b; Tao et al., 2003; Tzivion et al., 1994; Yin et al., 2000a,b, 2001;). Bin models also recently have been applied to marine stratocumuli (Feingold et al., 1999; Jiang et al., 2000, 2001, 2002). As illustrated in Figure 4.4, the Goddard Cumulus Ensemble model, as well as several other cloud models, can simulate multicell convective systems and be nested in the framework of larger-scale models and observational systems (Tao, 2003).

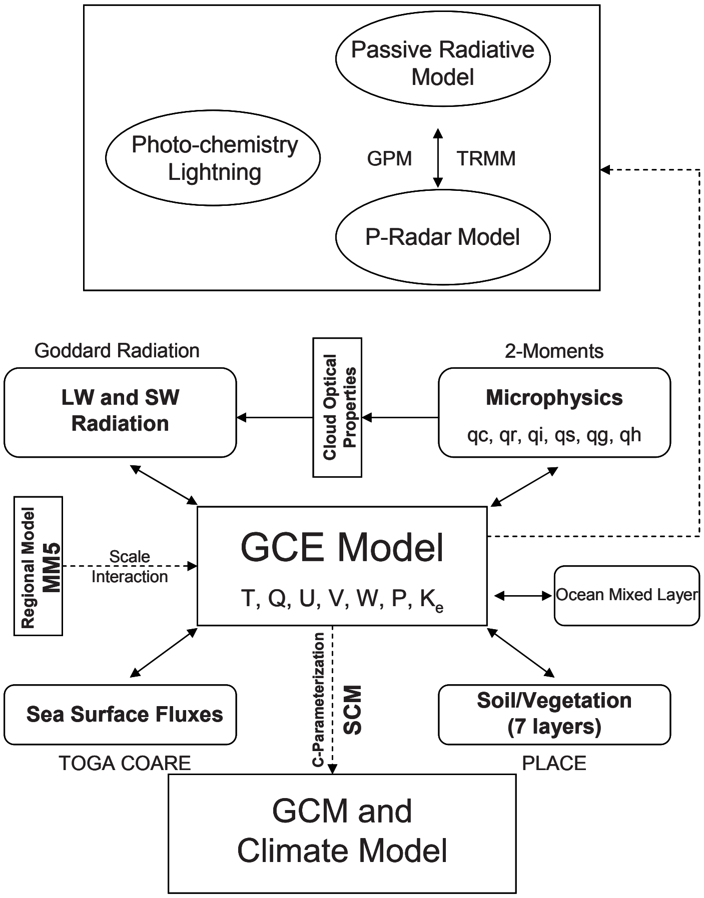

FIGURE 4.4 Schematic diagram showing the characteristics of the Goddard Cumulus Ensemble (GCE), a cloud-resolving model that includes explicit representation of warm rain and ice microphysical processes. Its main features are described in Tao et al. (2003). Arrows with solid lines indicate a two-way interaction between different physical processes and arrows with dashed lines indicate a one-way interaction. SCM stands for Single Column Model, a one-dimensional model with all GCM's physical processes. PLACE stands for Parameterization for Land-Atmosphere Cloud Exchange, a detailed interactive process model of the heterogeneous land surface and adjacent near-surface atmosphere. The model variables include horizontal (u, v) and vertical velocities (w), potential temperature (T), perturbation pressure (p), turbulent kinetic energy (Ke), and mixing ratios of all water phases [water vapor (Q), liquid (cloud water/qc, rain drops/qr), and ice (cloud ice/qi, snow/qs, graupel/qg, hail/qh)]. Recently, detailed spectral-bin microphysical schemes were implemented into the GCE model. The formulation for the explicit spectral-bin microphysical processes is based on solving stochastic kinetic equations for the size distribution functions of water droplets and several types of ice particles. Due to extensive computation, this microphysical scheme can only be run on the two-dimensional version of the model. SOURCE: Wei-Kuo Tao, NASA/Goddard Space Flight Center.

Current Status and Prospects

The most fully reported cloud simulation model relevant to nucleation, precipitation, and weather modification studies are the models of the two Israeli groups, one at the University of Tel Aviv developed by Tzivion and associates, the other at the Hebrew University of Jerusalem, developed by Khain and associates. The group at Tel Aviv focused more on the hygroscopic seeding agents, whereas at Jerusalem they focused more on the effect of variations in the natural and anthropogenic aerosol on the precipitation formation process. Yin et al (2001) found that seeding with hygroscopic flares produces changes in the hydrometeor distribution, with resulting changes in the radar reflectivity-rainfall rate relationship. Such changes are significant since radar is the primary evaluation tool for precipitation enhancement projects. Khain et al. (1999) report on simulations of cold season clouds over an eastern Mediterranean coastal zone in conditions of large-scale convergence that lead to significant precipitation. They concentrate attention on the effects of varying amounts (100, 500, and 1000 CCN cm^{-3}), vertical distributions (uniform or decreasing upward), and types (sodium chloride and ammonium sulfate) of condensation nuclei. They found that although most of the rain forms from melted snow or graupel, the larger drop sizes generated by the cleaner air (smaller CCN counts) produced rain much faster and that the total amount of rain was sensitive to the nucleus type (greater for ammonium sulfate). Neither of the results of the two groups could have been obtained by existing bulk model approaches.

Other modeling groups have adopted approaches to microphysical modeling similar to that of the Israelis. A major contributor is the NASA Goddard group, whose cloud-modeling results were recently summarized by Tao et al. (2003). The primary emphasis of the Goddard group is clouds and precipitation as major inputs to global and regional climatology, but here too the microphysical interactions are often crucial. For example, the formation of long-lived residual cirrus sheets is critical to the radiation budget, which then feeds back into the cloud dynamics. Also precipitation efficiency—the fraction of cloud liquid water that reaches the ground as rain—is important both for climatological and weather-forecasting purposes, and it apparently is strongly dependent on microphysical processes. Tao et al. (2003) report on three versions of microphysical simulation, including ice processes, two of them rather sophisticated bulk models and one a bin model. Most of the results shown are comparisons of models with each other, rather than with observations. Comparisons of bin model results with high and low CCN counts, in this case for entirely liquid clouds, indicate considerably greater rainfall for the clean air case.

Despite the progress that has been made, model predictions of hydrometeor evolution are not sufficiently accurate to inspire great confidence. Errors arise from limited resolution, insufficiently accurate physics, and inadequate observations. Bryan et al. (2003) point out that the typical resolution of simulated cloud and storm models, about 1 km, is insufficient to resolve the inertial range and predict dissipation. This is important because condensation, freezing, and coalescence appear to be dependent on at least the statistical structure of small-scale turbulence as principally defined by the dissipation rate. Resolution of order 100 m is found to be necessary for fairly accurate dynamical simulations, which stretches computer capabilities close to the limit, even without the best treatment of hydrometeors. Observational limitations include the resolution of humidity measurements and the very limited observational knowledge of the size and composition distribution of condensation nuclei and the distribution of temperatures at which freezing nuclei become effective. New methods of remote sensing may significantly improve the humidity observations, but the nuclei are only observable in situ from instrumentation at ground stations or on a few research aircraft, although alternative methods of nuclei retrieval are being explored. The model physics are again subject to computer limitations (and cleverness of design), but modeling of the interaction between ice and water species—and even between water drops themselves, whether the same size or not—rests on largely untested hypotheses.[1] Accurate prediction of the hydrometeor distribution development is critical to getting the dynamics-microphysics interaction correct, since hydrometeors determine (through sedimentation) the location and timing of latent heat release and precipitation loading impacts on cloud dynamics. It is exactly these details of the hydrometeor distribution development that cloud seeding tries to alter. Thus, while bin models have many degrees of freedom and thus can simulate many physical situations realistically, much of the knowledge necessary to specify parameters needed in their implementation is still lacking.

Data Assimilation, Model Initialization, and Advanced Forecasting Systems

Methods of optimally assimilating observed data and generating a series of fields suitable for initializing a prediction model have always been critical parts of large-scale numerical weather prediction, but at the convective scales, models have been under development for only 10 to 15 years. The potential for assimilation of fine-scale Doppler radar data, and from it establishing the dynamic and thermodynamic fields, was a major element of the proposal for the Center for Analysis and Prediction of Storms, one of the first of the NSF science and technology centers. Most of the methods developed or adapted by the Center's scientists and others are variational in nature, involving minimization of the integral of an error function. Among the most sophisticated is the adjoint method. The adjoint of a set of predictive equations is a similar set which predicts backwards the weightings of variables at a previous time which contribute to the change of a variable at a given position and current time. This allows, in principle, optimal utilization of current and previous data to produce an initial state for a future prediction. The adjoint method has shown fairly good success in obtaining three-dimensional initialization from single Doppler radar data (Sun and Crook, 1997, 2001; Xu et al., 1994), but it is rather expensive, often requiring the equivalent of 50 to 100 time integrations for a few minutes each. Methods for speeding the convergence are under active development.

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[1] For example, in a model with many different bins of ice and water species, the rate at which ice particles (of size 1 mm to 2 mm) combine with water droplets (of 1/8 mm to 1/4 mm) is a parameter that must be specified. This is a function of drop-size distributions, turbulence, temperature, the hydrodynamics of sedimentation, and, to a lesser extent, electrification of the cloud. Similar rate constants must be specified for all pairs of particle bins.

Future Prospects

Models and data assimilation offer the possibility of greatly ameliorating the difficulties of past statistical verification described in this report. With today's improved statistical techniques and sophisticated models, sources of uncertainty can be explicitly accounted for, and treatment and control experiments can now be compared spatially and temporally. The computational facilities and human resources necessary for work in these areas exist and can be rapidly developed at a number of governmental (e.g., NCAR, NOAA, NASA) and non-governmental laboratories and university groups for application to weather modification. Development of a cloud and precipitation model suitable for planning and testing seeding experiments may be feasible using the cutting edge of current simulation modeling. However, for real-time modeling studies that run coincidentally with field experiments a model would need to run faster (and therefore may be confined to a spatially coarser mesh and have less physical complexity) and would require data assimilation and initialization techniques that include microphysical parameters. Again, the techniques used for storm analysis and experimental prediction help point the way, although they have not been applied to the newer methods for observing water substance and phase, and methods need to be developed for rapid assimilation of these data types.

Model forecasts are always uncertain. Increasingly, predictions of large-scale models are presented as probabilities or ensembles. These probabilistic forecasts attempt to account for the uncertainties inherent in initial conditions, boundary conditions, and in the models themselves (especially the model parameterizations of subgrid-scale physical processes). Similar approaches should be used to quantify the uncertainty in simulations of weather modification experiments, including uncertainties related to the experimental treatment.

LABORATORY STUDIES

Laboratory investigations play an integral role in advancing the understanding of cloud physical processes. The high degree of measurement capability, repeatability, and control over experimental conditions in the laboratory allows research on detailed processes that is not possible in the free atmosphere.

Rogers and DeMott (1991) provide an excellent overview of the state of cloud physics laboratory work as of 1990. The most significant development in cloud physics laboratory studies since the early 1990s is the successful use of electrodynamic levitation chambers, in which nucleation and vapor deposition properties of individual, freely suspended hydrometeors can be studied in a fully controlled environment (Shaw et al., 2000; Swanson et al., 1999). Other important research continues on drop-drop interactions (Beard et al., 2001), on primary ice crystal habits and the impacts of growth and evaporation cycles (Bailey and Hallett, 2002), on nucleation coefficients of liquid and ice phases (Bailey and Hallett, 2002; Shaw and Lamb, 1999; Xue and Lamb, 2002), and on the growth of ice crystals in a water-saturated environment (Fukuta and Takahashi, 1999).

BOX 4.1
Hurricane Modeling and Prediction

As noted in DeMaria and Gross (2002), hurricanes present a particularly difficult modeling challenge in which a fairly small-scale, circularly symmetric disturbance (the storm) is embedded in a larger-scale surrounding flow. The lack of computer power and adequate observations, especially over the oceans, needed to properly represent initial conditions have been among the greatest difficulties in hurricane modeling.

More than 20 different types of hurricane models have been developed since 1959. Current hurricane simulations are limited to a resolution of about 10 km, with highly parameterized convection schemes. Using nested grid techniques, higher-resolution (~1 km), mixed-phase bulk microphysics models can be applied to small, critical regions in a hurricane, but until these high-resolution models can be applied to the entire domain of the storm system, only very basic aspects of hurricane modification theories can be tested.

Since the 1950s hurricane modeling has been divided into track-forecast models aimed at predicting where the storm will strike land, and intensity-forecast models aimed at predicting the strength and extent of the storm’s winds and consequent effects on the ocean (i.e., storm surge). Accurate track predictions require three-dimensional models that can account for the full range of interactions between the storm and its environment. Despite considerable advances in modeling hurricanes, the skill of track forecasts from a numerical model have only very recently overtaken that of statistical forecast methods (Emanuel, 2002). Average (24-hour) track errors remain above 70 miles for all models (DeMaria and Gross, 2002).

Modeling and forecasting the intensity of a hurricane remains an unresolved challenge. The present generation of models may not have enough horizontal resolution to capture the full intensity of extreme storms. However, new three-dimensional storm models (coupled to upper ocean models) should lead to better understanding of the factors that control hurricane intensity (Emanuel, 1999). Many other aspects of the hurricane system are not yet adequately modeled, including the areal extent of storm winds, the storm surge, and precipitation, especially flooding rainfall.

Improvement in theoretical and numerical modeling of hurricanes will undoubtedly remain a high national priority because of the value of predicting their behavior with increasing accuracy. Whether or not we can learn enough to consider modifying hurricanes to mitigate damage remains to be seen. Certainly, any attempt to modify hurricanes must be dependent upon whether their behavior with and without modification can be predicted accurately and reliably. Even then, any serious consideration of hurricane modification will raise grave and far reaching issues of public policy with both ethical and economic implications.

List et al. (1986) and Rogers and DeMott (1991) identified the need for a large national laboratory facility to study difficult simulation experiments such as the interactions between particles in the presence of aerosols or gases and electric fields. Such a facility has not yet been created, nor is there even any mechanism for long-term planning and funding of laboratory cloud physics research. As a result the number of cloud physics laboratory facilities in the nation has decreased in recent years, and there has been little influx of new talent. There is currently no coordinated effort to address the overall process of precipitation formation; rather, individual researchers address parts of the problem as permitted by their existing facilities. In particular, there appears to be no ongoing investigation of ice or ice interactions, and only limited facilities to study mixed-phase processes.

There are, of course, constraints on the types of problems that can be addressed through laboratory studies; thus the greatest progress can be made when laboratory studies are linked to theoretical and numerical modeling studies and observational work.

FIELD STUDIES

Physical concepts, laboratory findings, and numerical models must ultimately be tested in the field. Field studies have the unique capability of concentrating analytical and technical tools on a specific problem in a given time and space domain. Progress in understanding the chain of physical processes leading to precipitation or underlying severe weather has isolated key uncertainties, as identified in earlier sections. These uncertainties constitute goals that can be addressed in a hierarchy of field studies. Such studies progress from limited activities that can build on other atmospheric field programs to dedicated large-scale weather modification experiments. Crucial uncertainties inherent in the exploitation of atmospheric resources and mitigation of weather hazards (Box 2.2) need to be addressed if larger-scale, dedicated weather modification experiments are to make substantial advances. Such field studies must be founded upon testable physical hypotheses and must advance stepwise from the simplified to the more complex. It should be noted that scientists at the Mazatlan workshop (discussed in Appendix A) identified a number of specific, testable hypotheses that could form a useful basis for future field experiments (WMO, 2000).

Because many of the roadblocks impeding progress in weather modification are part of the wider research problems facing atmospheric science as a whole, these studies may be pursued on a broad front. Cloud formation, precipitation generation, and the dynamics of severe weather are all of interest to a large number of atmospheric scientists. Opportunities thus abound for the pursuit of basic studies of critical concern to weather modification. What is lacking is a centralized program to coordinate this research as a national effort in atmospheric resource enhancement and weather hazard mitigation. Such a program could coordinate modeling, laboratory, and field studies that range from modest “piggyback” experiments to full-blown, dedicated field studies for testing and demonstrating weather modification procedures.

These field studies need to be sustained and would benefit from centralized long-lived facilities. Such centralized and essentially permanent facilities exist at NCAR, NOAA/ETL, and the U.S. Southern Great Plains CART established on the Oklahoma/Kansas border by the DOE ARM Program. NCAR has a long history of basic and applied research in weather modification with advanced computer and observing facilities designed to serve the atmospheric research community. Similarly, NOAA/ETL has contributed significant funding toward weather modification research efforts in the past. The CART/ARM site has an extensive array of observing systems detailed in Table 4.1. NASA is planning as part of the GPM to significantly enhance the CART/ARM site.

This array of observing systems with its attendant infrastructure presents an unprecedented opportunity to pursue fundamental questions facing the weather modification community. While the Oklahoma/Kansas location will not address all problems of weather modification research, fundamental questions involving the formation of precipitation, the distribution and nature of cloud liquid water and ice in large convective storms, and a host of other more sophisticated experiments, which could involve actual treatment, are among important problems that can be tackled. The combined capabilities at NCAR, NOAA/ETL, and the CART/ARM/GPM site constitute an opportunity that may only require financial and logistical coordination by a central agency to provide a powerful base for weather modification field studies.

A number of other operational networks and facilities are available that can advance studies in weather modification; for instance,

- operational facilities of the National Weather Service (NWS) could be used to conduct comparative, parallel climatological studies in different geographic regions;
- the national operational Doppler weather radar network (NEXRAD) might be useful in characterizing cloud and precipitation climatologies in neighboring treated and untreated regions in operational weather modification programs;
- the Oklahoma Mesonet (Brock et al., 1995) provides high-resolution meteorological data for research, educational, operational, and commercial purposes; and
- the Automated Surface Observing System, operated by the NWS and the Federal Aviation Administration, is a highly sophisticated surface network that provides high-quality data routinely at approximately 1,000 sites (mostly at airports) across the United States.

Ongoing operational programs in weather modification can be improved by the addition of research components. Ultimately, however, major issues of atmospheric resource use and hazard mitigation must be addressed by a sustained research effort. Such a sustained effort ideally rests on an infrastructure of administrative, logistical, numerical, laboratory, and field support coordinated under a single program.

TABLE 4.1 ARM/CART Site Instruments

Purpose or parameter measured	System (if applicable)	Instrument
Aerosols	Aerosol observation system	n/a
	Additional systems	Cimel sunphotometer Multifilter rotating shadowband Radiometer Raman lidar
Atmospheric profiling		Balloon-borne sounding system Microwave radiometer Raman lidar 50 MHz radar wind profiler and radio acoustic sounding system (RASS) 915 MHz radar wind profiler and RASS
Clouds		Belfort laser ceilometer Micropulse lidar Millimeter-wavelength cloud radar Microwave radiometer Video time-lapse camera Whole-sky imager Narrow field-of-view sensor Raman lidar
Radiometers		Atmospheric emitted radiance interferometer Absolute solar transmittance interferometer Cimel sunphotometer Infrared thermometer Microwave radiometer Narrow field-of-view sensor Rotating shadowband spectrometer Shortwave spectrometer Solar radiance transmission interferometer
	MFRSR-related	Multifilter rotating shadowband radiometer MFR (upwelling)
	Broad-band instruments	Pyranometers Pyrgeometers Pyrheliometers UV-B radiometer UV spectroradiometer
	Radiometric instrument systems	Solar infrared radiation station

Surface energy flux		Eddy correlation system Energy balance Bowen ratio station Infrared thermometer Soil water and temperature system
Surface meteorology		Chilled mirror Surface meteorological observation system instruments 60-m tower: temperature and humidity sensors Temperature, humidity, wind, and pressure sensors
Instruments of extended facilities of the CART/ARM site	Radiometers	Solar infrared radiation station Multifilter rotating shadowband radiometer
	Surface energy flux	Eddy correlation systems Energy balance Bowen ratio stations Soil water and temperature system
	Surface meteorological observation system instruments	n/a
Instruments at boundary facilities of the CART/ARM site		Balloon-borne sounding system Microwave radiometer Vaisala ceilometer Atmospheric emitted radiance interferometer Temperature, humidity, wind, and pressure sensors
Instruments at intermediate facilities of the CART/ARM site		915-MHz radar wind profiler Radio acoustic sounding system

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Conclusions and Recommendations

Although 40 years have passed since the first NAS report (NRC, 1964) on weather modification, this Committee finds itself very much in concurrence with the findings of that assessment (see Chapter 1).

> We conclude that the initiation of large-scale operational weather modification programs would be premature. Many fundamental problems must be answered first. It is unlikely that these problems will be solved by the expansion of present efforts, which emphasize the a posteriori evaluation of largely uncontrolled experiments. We believe that the patient investigation of atmospheric processes coupled with an exploration of the technological applications may eventually lead to useful weather modification, but we emphasize that the time-scale required for success may be measured in decades.

CONCLUSIONS

Below is a summary of the Committee's principal conclusions, presented in response to the tasks that the Committee was asked to address.

Task 1: Review the current state of the sciences of weather modification and the role of weather prediction as it applies to weather modification, paying particular attention to the technological and methodological developments of the last decade.

Principal conclusion. Over the past 30 years, there has been significant advancement in observational and computational capabilities, providing new opportunities to address many of the outstanding questions underlying attempts to modify weather. **It is the principal conclusion of this Committee that the field of atmospheric science is now in a position to mount a concerted and sustained effort to delineate the scope and expectations of future weather modification research. Such an effort must be directed at answering fundamental scientific questions that will yield results that go well beyond application to intentional modification. The emphasis must be on understanding processes and not on modification.** Once understanding is achieved, the focus can turn to application of this understanding, not only to intentional weather modification but also to inadvertent modification and other related fields, such as cloud modeling and weather forecasting.

Status of weather modification research. Weather modification research has been in a state of decline in the United States for more than two decades. The reasons are many and include the lack of scientifically demonstrable success in modification experiments, extravagant claims, attendant unrealistic expectations (e.g., pressure from agencies to meet short-term operational needs rather than to achieve long-term scientific understanding), growing environmental concerns, and economic and legal factors. Within this context it became difficult to distinguish legitimate and important research from some cloud-seeding programs claiming success with little or no substantiation. This led many scientists to abandon the field and federal agencies to reduce funding for weather modification research dramatically.

Status of weather modification operations. Despite the decline in research in the United States, weather modification remains a topic of substantial worldwide interest, with programs currently active in more than 24 countries. In the United States in 2001 there were at least 66 operational programs (supported by private and state entities) aimed at enhancing rain, enhancing snowpack, or suppressing hail. Evaluation methodologies vary but in general do not provide convincing scientific evidence for either success or failure. Although there is physical evidence that seeding affects cloud processes, effective methods for significantly modifying the weather generally have not been demonstrated.

Scientific evidence of seeding effects. The Committee concurs with the conclusion from Silverman (2001) that: "Based upon a rigorous examination of the accumulated results of the numerous experimental tests of the static-mode and dynamic-mode seeding concepts conducted over the past four decades, it has been found that they have not yet provided either the statistical or physical evidence required to establish their scientific validity." This statement was made specifically in reference to glaciogenic seeding of convective clouds. With the possible exception of winter orographic clouds, it applies to virtually all efforts aimed at precipitation enhancement or hail suppression. This does not challenge the scientific basis of cloud-seeding concepts; rather, it is recognition of the lack of credible evidence that applying these concepts will lead to predictable, detectable, and verifiable results.

Recent experiments have renewed interest in the possibility of increasing rainfall from warm season convective clouds by cloud-base release of hygroscopic particles. These particles have just the right characteristics to promote the formation of drizzle, which grows by coalescence into rain. There have been promising experiments conducted in South Africa and in Mexico, where measurements using new observing systems have demonstrated responses in clouds to treatment in accordance with understanding of the chain of physical reactions leading to precipitation. This appears to be a fruitful area for further research.

Hazard mitigation. In the arena of hazard mitigation there are at least two examples of success. The suppression of cold fogs is clearly established and is used effectively at airports and other select locations. The use of lightning rods is an exceptionally effective method for protecting property, but no scientifically acceptable evidence exists that lightning can be suppressed or redirected through deliberate interventions in atmospheric processes. The inadvertent effect of air pollution on the frequency and polarity of cloud-to-ground lightning strikes is an important new finding supported by some observations.

There is no scientifically credible evidence that hail can be suppressed. Lack of knowledge and ability to observe the details of a large hailstorm limits our ability to target observations or to design experiments that can detect induced changes. Insurance data showing reduced crop damage in areas of hail suppression activity may serve to motivate the operational programs, but they do not constitute scientific proof that hail fall can be reduced.

Almost no work has been conducted aimed at tornado mitigation. All work on modifying hurricanes, including numerical model simulations, ceased in 1980. Past hurricane modification studies contributed substantially to the knowledge of the structure and inner workings of hurricanes, which led to improvements in forecasting hurricane motion and intensity. However, a detailed understanding of the dynamics, thermodynamics, and cloud physics of hurricanes must be attained before any actual modification experiments are considered.

Atmospheric modeling and weather forecasting. Numerical simulation and prediction models are key components of a national weather modification program for use in planning and justification, operations, and post-operation analysis. Simplified simulation models may be useful for learning about the sensitivity of a cloud system to various kinds of modification, while a prediction model must be able to conform to real initial and boundary conditions. The success of any weather modification program can best be tested by comparison with a prediction of what would have happened without the modification. However, this places an enormous burden on prediction since many of the uncertainties limiting quantitative precipitation forecasting in weather forecast models and cloud parameterizations are the same as those that limit understanding of the physics and dynamics of seeded clouds. Thus, further advancement of numerical modeling capabilities is necessary, but weather modification-related research should not await an ability to make quantitative precipitation forecasting predictions. Improving modeling and quantitative precipitation forecasting are long-term, iterative processes that will continue to evolve for decades to come. In the meantime, there is a tremendous amount that can be learned by addressing other relevant research questions (e.g., precipitation formation mechanisms, cloud/storm dynamics). In fact, developments in these basic physical processes and in precipitation forecasting would benefit if done commensurately.

Operational and mesoscale predictions, supplemented by a program of numerical modeling and prediction aimed at resolving the much smaller scales of clouds (finer than 1 km) and incorporating the detailed physics of precipitation processes and evolution, would be useful for developing a research-quality weather modification program. The quality and validity of such cloud models have also improved substantially in the last two decades due to great increases in computer power and improved mathematical and numerical methods, including those for data assimilation. The models have not yet, however, demonstrated the ability to accurately represent and predict precipitation processes under all important natural conditions. Bin microphysics, which is believed to be the best current method for simulating cloud nucleus and hydrometeor evolution, is computationally demanding. It is currently on the borderline of practical utility for simulating large convective clouds but may be more fully usable for simulating winter orographic clouds. Full testing of such models remains difficult because of the inadequacy of direct measurement of cloud water and nucleus properties, though satellite and other remote-sensing observation methods help fill in the details. Evidence from the best simulation models indicates that precipitation-forming processes may be strongly dependent on the size spectrum of existing condensation and freezing nuclei, and that artificial modifications of nuclei concentrations may produce predictable results.

Observational technologies. There have been many advances in observational technologies in the past two decades. New remote and *in situ* approaches have dramatically improved the ability to examine the structure and hydrometeor content of clouds. Polarization-diversity radars can estimate in-cloud particle shapes and sizes, allow tracking of the dispersion of seeding aerosols, and allow more accurate estimates of precipitation. Millimeter-wave cloud radar can describe non-precipitating clouds. The national Doppler radar network (NEXRAD) provides opportunities for examining the evolution of radar signatures in all regions of the country, and for applying cell tracking capabilities in field experiments designed to test hypotheses relevant to cloud microphysical processes. Satellites provide observations of background aerosol and cloud microstructure as well as seeding signatures to be obtained. Applying these new observational technologies coherently can greatly advance our understanding of many key processes relevant to weather modification.

Task 2: Identify the critical uncertainties limiting advances in weather modification science and operation.

Scientific and methodological uncertainties. The science underlying weather modification is replete with uncertainties and knowledge gaps. These include fundamental microphysics, the effectiveness of seeding methodologies, and the verifiability of modification procedures. At the most basic level important questions remain regarding liquid and ice nuclei numbers and nucleation processes; the presence, concentration, and location of supercooled water in clouds; droplet and hydrometeor evolution processes; and the natural variability of all these factors.

Methodological uncertainties are related to the effectiveness of particular seeding materials, the dispersion of seeding materials in clouds, interactions between clouds and cells within the same cloud system, effects outside of seeded areas, separation of the seeding effects from natural effects, and the use of surrogate measurements such as radar reflectivity factors to observe cloud and precipitation changes. The uncertainties of greatest interest to users of weather modification technologies relate to evaluation of the seeding effects, namely, the determination of whether any significant effect on such things as rainfall or hail fall actually occurred. Improved statistical evaluation techniques could be beneficial in addressing this problem.

By recognizing these uncertainties one can more readily identify the crucial gaps in understanding that impede progress in weather modification. Such issues are equally important to fundamental research in cloud physics and radiation, weather forecasting, and anthropogenic climate change. Opportunities abound for collaboration among these various fields of interest.

Task 3: Identify future directions in weather modification research and operations for improving the management of water resources and the reduction in severe weather hazards.

Opportunities for future progress. Given the lack of scientific evidence and the critical uncertainties, weather modification methodologies do not guarantee desired results. Therefore, from a scientific perspective these technologies do not appear ready for immediate application in water resource management or hazard mitigation strategies. Nevertheless, there are many advances in observing, computing, modeling, and statistics, all of which offer a means to establish hypotheses and evaluation criteria and to address many of the uncertainties that limit our confidence in weather modification approaches for operational use. Until this is done operational cloud-seeding programs likely will continue to make their decisions based on probabilistic cost-versus-benefit analyses subject to considerable speculation.

Use of existing resources. Existing national facilities such as the NEXRAD network, NCAR, NOAA/ETL, and the ARM/CART site could be used for fundamental cloud studies and as pilot program test-beds. Advanced computing capabilities enable high-resolution modeling, and community models at NCAR and models at several universities are available for researchers to use at their home institutions. These new tools form the basis of a coordinated program (WMO, 2000) in weather modification research. In addition, existing operational weather modification programs offer opportunities for focused research, and such collaborations are likely to be welcomed by the operational groups. It is, of course, important to ensure that such research be evaluated independently to provide a more robust assessment of the results.

Task 4: Suggest actions to identify the potential impacts of localized weather modification on large-scale weather and climate patterns.

Effects outside of seeded areas. There still is no convincing scientific evidence of the efficacy of intentional weather modification efforts, and there is even less evidence that weather modification efforts affect weather outside of the seeded regions. Questions about whether cloud seeding in one location can reduce precipitation in other areas can only be addressed through carefully crafted hypotheses and carefully designed physical and statistical experiments. Since the direct effects of seeding may be small and difficult to detect, measuring effects outside of the seeded areas as well as regional or global effects is likely to be even more difficult. Numerical modeling simulations—validated by observations whenever possible—may prove to be a useful means for testing larger-scale effects, and it offers the best approach for examining the potential for inadvertent modification occurring as a consequence of intentional seeding. In addition, new satellite-remote-sensing capabilities and the NEXRAD network may allow the identification of some changes in cloud structure and precipitation, which may lead to substantive improvements in our current understanding of effects outside of the seeded areas.

Inadvertent weather modification. There is ample evidence that inadvertent weather and global climate modification (e.g., greenhouse gases affecting global temperatures and anthropogenic aerosols affecting cloud properties) is a reality. The role of natural and anthropogenic aerosols in influencing cloud drop size, precipitation, and lightning on regional scales has been increasingly observed and studied. Documentation of anthropogenic effects on the weather strengthens the physical basis for deliberate attempts to alter the weather. In addition, the changing levels of background aerosols associated with inadvertent weather modification can influence the potential for deliberate weather modification. Therefore, cross-over studies of advertent and inadvertent modification will contribute to the understanding of both kinds of weather modification.

RECOMMENDATIONS

Recommendation: Because weather modification could potentially contribute to alleviating water resource stresses and severe weather hazards, because weather modification is being attempted regardless of scientific proof supporting or refuting its efficacy, because inadvertent atmospheric changes are a reality, and because an entire suite of new tools and techniques now exist that could be applied to this issue, the Committee recommends that there be a renewed commitment to advancing our knowledge of fundamental atmospheric processes that are central to the issues of intentional and inadvertent weather modification. The lessons learned from such research are likely to have implications well beyond issues of weather modification. Sustainable use of atmospheric water resources and mitigation of the risks posed by hazardous weather are important goals that deserve to be addressed through a sustained research effort.

Recommendation: The Committee recommends that a coordinated national program be developed to conduct a sustained research effort in the areas of cloud and precipitation microphysics, cloud dynamics, cloud modeling, and cloud seeding; it should be implemented using a balanced approach of modeling, laboratory studies, and field measurements designed to reduce the key uncertainties listed in Box 2.2. This program should not focus on near-term operational applications of weather modification; rather it should address fundamental research questions from these areas that currently impede progress and understanding of intentional and inadvertent weather modification. Because a comprehensive set of specific research questions cannot possibly be listed here, they should be defined by individual proposals funded by the national program. Nevertheless, examples of such questions may include the following:

- What is the background aerosol concentration in various places, at different times of the year, and during different meteorological conditions? To what extent would weather modification operations be dependent on these background concentrations?
- What is the variability of cloud and cell properties (including structure, intensity, evolution, and lifetime) within larger clusters, and how do clouds and cells interact with

larger-scale systems? What are the effects of localized seeding on the larger systems in which the seeded clouds are embedded?

- How accurate are radar reflectivity measurements in measuring the differences between accumulated rainfall in seeded and unseeded clouds? How does seeding affect the drop-size distribution that determines the relationship between the measured radar parameter and actual rainfall at the surface?

The tasks involved in weather modification research fall within the mission responsibilities of several government departments and agencies, and careful coordination of these tasks will be required.

Recommendation: The Committee recommends that this coordinated research program include:

- **Capitalizing on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems** (e.g., Doppler lidars and airborne radars, microwave radiometers, millimeter-wave and polarimetric cloud radars, GPS and cell-tracking software, the Cloud Particle Imager, the Gerber Particle Volume Monitor, the Cloud Droplet Spectrometer). Initial field studies should concentrate on areas that are amenable to accurate numerical simulation and multiparameter, three-dimensional observations that allow the testing of clearly formulated physical hypotheses. Some especially promising possibilities where substantial further progress may occur (not listed in any priority) include

    - ➢ *Hygroscopic seeding to enhance rainfall.* The small-scale experiments and larger-scale coordinated field efforts proposed by the Mazatlan workshop on hygroscopic seeding (WMO, 2000) could form a starting point for such efforts. A randomized seeding program with concurrent physical measurements (conducted over a period as short as three years) could help scientists to either confirm or discard the statistical results of recent experiments.

    - ➢ *Orographic cloud seeding to enhance precipitation.* Such a program could build on existing operational activities in the mountainous western United States. A randomized program that includes strong modeling and observational components, employing advanced computational and observational tools, could substantially enhance our understanding of seeding effects and winter orographic precipitation.

    - ➢ *Studies of specific seeding effects.* This may include studies such as those of the initial droplet broadening and subsequent formation of drizzle and rain associated with hygroscopic seeding, or of the role of large (>1 μm) particles (e.g., sea spray) in reducing droplet concentrations in polluted regions where precipitation is suppressed due to excess concentrations of small CCN.

- **Improving cloud model treatment of cloud and precipitation physics.** Special focus is needed on modeling cloud condensation nuclei, ice nuclei processes, and the growth, collision, breakup, and coalescence of water drops and ice particles. Such studies must be based on cloud physics laboratory measurements, tested and tuned in model studies, and validated by in situ and ground observations.

- **Improving and using current computational and data assimilation capabilities.** Advances are needed to allow rapid processing of large quantities of data from new observations and better simulation of moist cloud and precipitation processes. These models could subsequently be used as planning and diagnostic tools in future weather modification studies and to develop techniques to assist in the evaluation of seeding effects.

- **Capitalizing on existing field facilities and developing partnerships among research groups and select operational programs**. Research in weather modification should take full advantage of opportunities offered by other field research programs and by operational weather modification activities. Modest additional research efforts directed at the types of research questions mentioned above can be added with minimal interference to existing programs. A particularly promising opportunity for such a partnership is the DOE ARM/CART site in the southern Great Plains (Oklahoma/Kansas) augmented by the NASA Global Precipitation Mission. This site provides a concentration of the most advanced observing systems and an infrastructural base for sustained basic research. The NCAR and NOAA/ETL also could serve as important focal points for weather modification research.

In pursuing research related to weather modification explicit financial and collegial support should be given to young aspiring scientists to enable them to contribute to our fundamental store of knowledge about methods to enhance atmospheric resources and reduce the impacts of hazardous weather. It must be acknowledged that issues related to weather modification go well beyond the limits of physical science. Such issues involve society as a whole, and scientific weather modification research should be accompanied by parallel social, political, economic, environmental, and legal studies.

Closing Thoughts

The Committee emphasizes that weather modification should be viewed as a fundamental and legitimate element of atmospheric and environmental science. Owing to the growing demand for fresh water, the increasing levels of damage and loss of life resulting from severe weather, the undertaking of operational activities without the guidance of a careful scientific foundation, and the reality of inadvertent atmospheric changes, the scientific community now has the opportunity, challenge, and responsibility to assess the potential efficacy and value of intentional weather modification technologies.

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A

Glaciogenic and Hygroscopic Seeding: Previous Research and Current Status

Details of the methods and findings stemming from research employing or relating to glaciogenic and hygroscopic seeding are discussed below. The glaciogenic seeding approach is divided into static and dynamic seeding, and separates convective from layered or stratiform cloud processes.

PREVIOUS RESEARCH

Glaciogenic Seeding Experiments

Static Seeding: Convective Clouds

Since convective storms produce a significant percentage of the rainfall occurring over many parts of the world, these cloud systems have been the subject of numerous seeding experiments to test the static seeding concepts. The best-known early experiments on convective clouds were the Arizona Projects (Battan and Kassander, 1967), the Israeli experiments (Gagin and Newmann, 1974), and the Whitetop experiment (Braham, Jr., 1964, 1979). Measurements of physical variables were made on all three projects, but they were limited by the crude measurement systems available at the time. These measurements helped in the interpretation of the statistical results and placed the physical concept on a firmer scientific base (Cotton, 1986). The experiments used area-wide seeding with silver iodide dispensed from airplanes flying at cloud-base levels upwind of the target areas. Although statistical significance was not achieved in Whitetop, the data indicated a decrease in rainfall following seeding. This result also was reported in the Arizona experiment (Battan and Kassander, 1967; Neyman et al., 1972).

Smaller cloud systems were often used as the experimental units in order to minimize the complexity of the dynamic framework. Many of the experiments used a combination of physical measurements and statistics to investigate the early links in seeding-induced changes to the rainfall formation process. Although several of these experiments showed that it was possible to alter the initial steps of the precipitation formation process, it was more difficult to prove that these changes translated to increased precipitation on the ground. The experimental units, due to their size, were often not significant contributors to precipitation in the area. Results based on smaller clouds might not be transferable to more dynamically vigorous cloud complexes.

Some of the initial steps in the chain of events of precipitation formation that have been demonstrated in field measurements and laboratory and modeling studies include increased concentrations of ice crystals and the more rapid production of precipitation particles in cumulus clouds. In the High Plains Experiment (HIPLEX-1), a detailed seeding hypothesis (Smith et al., 1984) guided a well-designed field program that monitored each step in the physical hypothesis. Although the experiment failed to demonstrate statistically all the hypothesized steps, the problems could be traced to the physical dataset (Cooper and Lawson, 1984). This in itself, is a significant result that shows the ability of physical measurements and studies to provide an understanding of the underlying processes in each experiment. The results suggested that a more limited window of opportunity exists for precipitation enhancement than was thought previously. Cotton and Pielke (1995) summarized this window of opportunity notion as being limited to

- clouds that are relatively cold-based and continental;
- clouds having top temperatures in the range –10 °C to –25°C; and
- a timescale confined to the availability of significant supercooled water before depletion by entrainment and natural precipitation processes.

It was recognized in HIPLEX that small clouds would make very little contribution to rainfall. The study of larger cloud complexes planned as part of HIPLEX was not completed when the experiments were prematurely halted. However, important microphysical findings did emerge from the study of the smaller clouds.

The Israeli glaciogenic precipitation enhancement experiments, based on the static seeding concept as applied to winter cold-front and post-frontal cloud bands (with embedded convection), initially provided strong evidence of increases in precipitation on the ground (Gagin and Neumann, 1981). These experiments eventually became the subject of a scientific debate initiated by Rangno and Hobbs (1995). The validity of the results was questioned and alternative reasons were presented for the results: a Type I statistical error (lucky draw) in Israeli I and natural variability in rainfall in Israeli II. The likelihood of the Type I error eventually was shown to be equal to the statistical significance level, and the mixed results of the Israeli II experiment were discussed (Gabriel and Rosenfeld, 1990) and further explanation using physical-statistical analyses was given (Rosenfeld and Farbstein, 1992; Rosenfeld and Nirel, 1996; Levi and Rosenfeld, 1996). An important lesson to learn from this debate is to measure and record all possible physical variables in the chain of events in precipitation formation, in order to support the results of any statistical experiment. Silverman (2001), in his review of glaciogenic seeding experiments, highlights some of the shortcomings of the statistical design and execution of these experiments.

Static Seeding: Winter Orographic Clouds

Experiments to seed wintertime orographic clouds for precipitation enhancement (snowpack and rainfall augmentation) have highlighted the complex interaction between the terrain and the wind-flow structure in determining regions of cloud liquid water (CLW) and also in targeting and dispersing seeding material. This interaction explains the difficulty experienced in showing cause and effect through seeding experiments over the Sierra Nevada (Deshler et al., 1990).

Changes in the concentrations of precipitating ice crystals, ice nuclei, and precipitation rate have been observed after seeding in topographically forced regions (Figure A.1). In some experiments seeding has produced strong evidence of precipitation increases, including the Tasmanian experiments when cloud top temperatures were between –10°C and 12°C in southwesterly airflow (Ryan and King, 1997). Additionally, results from the Bridger Range experiment showed an order of magnitude increase in ice particle concentration—contingent upon available supercooled liquid water—leading to increased precipitation. In such experiments the biggest challenge, again, is to collect sufficient physical data on the links in the chain of events to support statistical results.

The results from the CLIMAX I and CLIMAX II experiments (Grant and Mielke, 1967; Mielke et al., 1981), which were the most compelling evidence in the United States for enhancing precipitation in wintertime orographic clouds, were also challenged by Rangno and Hobbs (1987, 1993). Although the Rangno and Hobbs reanalyses indicate a possible increase in precipitation of about 10 percent, which is less than originally reported, it still is a significant amount. Cotton and Pielke (1995) noted that the design, implementation, and analysis of this experiment were clearly a learning process, not only for meteorologists but also for statisticians. Many of the cloud systems in orographic snowpack enhancement programs were not simply "blanket-type" orographic clouds, but most often they were part of major winter cyclonic storms with continuously changing wind-flow regimes and cloud structures, including both temporal- and spatial-changing CLW regions (Rauber et al., 1986, Rauber and Grant, 1986). Mesoscale numerical models (Bruintjes et al., 1994; 1995), sophisticated radars, microwave radiometers, and tracer studies could help substantially in identifying the spatial and temporal changes in cloud structures and associated seeding potential (Klimowsky et al., 1998; Reinking et al., 1999, 2000; Huggins, 1995). These advances are discussed in more detail in Chapter 4.

The chemical and physical properties of aerosols are important in determining ice formation rates and efficiency. This fact led to the development of new, highly efficient silver chloro-iodide ice nuclei (DeMott et al., 1983). These nuclei can be generated with a soluble component to enhance the action of a fast condensation-freezing ice nucleation mechanism (Feng and Finnegan, 1989). In addition, new formulations of fast acting, highly efficient ice nuclei from pyrotechnic devices continued in the 1990s. These new ice-nucleating agents, effective at temperatures below –4°C, represent substantial improvements over prior ice nuclei generation capabilities and offer possibilities for engineering nuclei with specific desirable properties (Figure A.2).

New methods for detecting small quantities of seeding agents in snowpack and rainwater also have been recently demonstrated, along with the use of tracer and nuclei ratio techniques to evaluate seeding effects (Warburton et al., 1995). Warburton also showed that the dispersion of silver iodide in orographic winter clouds could have

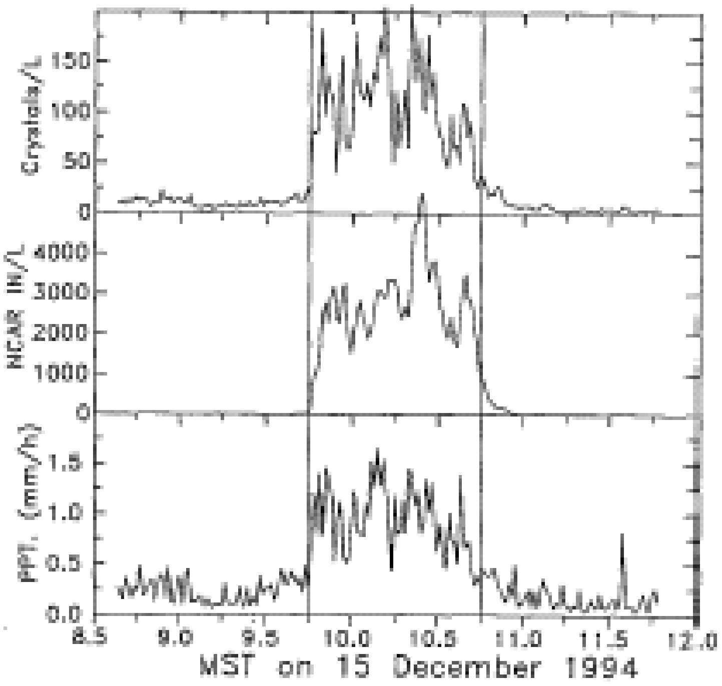

FIGURE A.1 Observed concentrations of precipitating ice crystals, ice nuclei, and precipitation rate during one hour of AgI seeding between 0945 and 1045, December 15, 1994 in Utah. SOURCE: Super and Halroyd (1997).

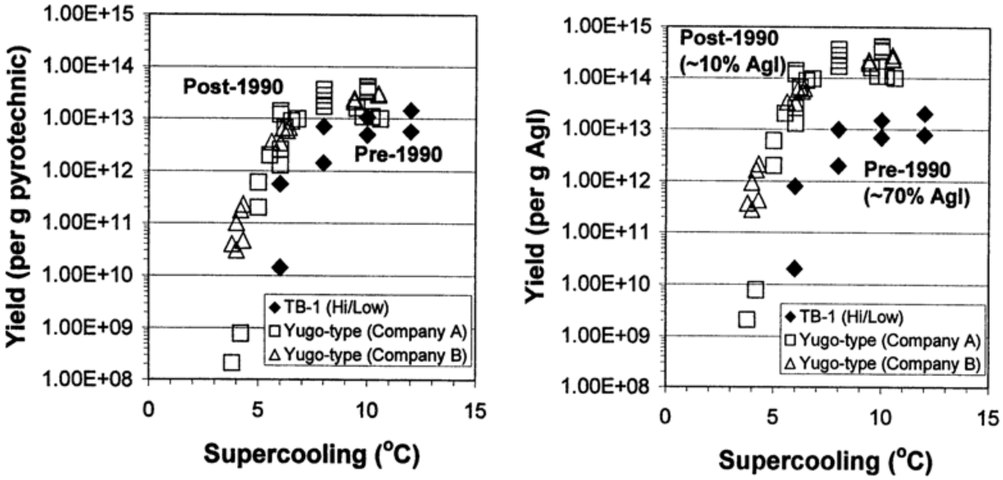

FIGURE A.2 New Pyrotechnic Developments. Yield per gram of pyrotechnic (left panel) and yield per gram of silver iodide (right panel) of ice formation by new pyrotechnic glaciogenic seeding generators prior to (TB-1) and since about 1990. The new type of generators/flares are more efficient in producing ice nuclei on a compositional basis, require less silver iodide (as $AgIO_3$), and "react" much faster in a water-saturated cloud. Results are from records of Colorado State University isothermal cloud chamber facility.

actively participated in the nucleation of 15 percent to 30 percent of the ice crystals that formed the snowpack.

Dynamic Seeding

Project Stormfury was among the earliest dynamic seeding experiments carried out on oceanic cumulus clouds. It was pioneering in that it was based on a numerical model of cumulus dynamics with a complete set of physical and dynamical equations. The Florida Area Cumulus Experiments (FACE-1 and FACE-2) also are typical examples of the early dynamic seeding experiments (Woodley et al., 1982, 1983; Gagin et al., 1986). The complexity of the chain of physical links leading to precipitation, together with difficulties in observing these processes, led to the adoption of a statistical approach as proof of concept. Initial encouraging results led to several other experiments designed along similar lines. Experiments in Texas using radar-defined floating targets showed increases in areas, duration, and rain volume but only slightly in cloud heights. Although the radar-defined floating target analyses indicated increases in rain volume, fixed ground-target analyses yielded no significant results. To explain the less-than-expected increases in cloud tops, the dynamic seeding hypothesis was consequently modified to include more details of microphysical processes and to emphasize the rapid conversion of supercooled liquid water (and especially large drops) into graupel in the seeded plume (Rosenfeld and Woodley, 1993). The nature of the hypothesis is such that it might be difficult to measure and verify the different links, especially in the vigorous cloud systems that are used as experimental units. However, the new cloud physics instruments and remote-sensing devices that distinguish between water and ice hydrometeors make documentation more feasible; furthermore, cloud models can be used to test this conceptual model.

Since 1980 operational and research glaciogenic seeding experiments for rainfall enhancement based on the dynamic seeding concept have been conducted in Texas, Cuba, South Africa, and Thailand. Exploratory analyses of these experiments have indicated precipitation increases on the scale of individual clouds or cells with varying levels of statistical support. The evidence for area-wide effects, although suggestive of precipitation increases, is weak and lacking in statistical support. No one has yet run a definitive area-seeding experiment.

More recently (1994–1998) a randomized convective cloud-seeding experiment was conducted on mixed-phase clouds in Thailand, based on the dynamic seeding concept. The sample consisted of 62 units, and while the statistical results indicated increases in rainfall, the results were not statistically significant (Woodley et al., 1999). The authors stated before commencement of the experiment that 125 units were needed to provide confidence in the statistical results (i.e., the sample size needed to be able with sufficient power to detect a difference that is statistically significant, assuming that approximately half the sample was treated and the other half was not treated). The number of experimental units required in a randomized experiment to achieve confidence in the statistical results is a factor that needs careful consideration by funding agencies, as several projects have come to an end before this number has been reached (e.g., FACE-2), leaving the results indeterminate.

In recent years the importance of coalescence (and hence aerosols) on cloud structure, evolution, and rain production has been emphasized and highlighted in the dynamic seeding conceptual model (Rosenfeld and Woodley, 1993). It is known that clouds in "continental" air masses with high concentrations of cloud droplets (e.g., ≥ 500 cm^{-3}) can sometimes retain regions where water remains supercooled to the point of homogeneous nucleation (–38°C; see Rosenfeld and Woodley, 2000), with freezing taking place abruptly once the colder temperatures are reached in agreement with laboratory studies. Continental clouds take twice as long (i.e., they must reach colder temperatures) to glaciate as maritime clouds having initial cloud droplet concentrations between 100 cm^{-3} and 300 cm^{-3}, providing a potential "window" for glaciogenic seeding intervention (Orville, 2001).

These observations of extreme supercooling (Rosenfeld and Woodley, 2000) seem to be in contrast with many other measurements which have found the initial ice formation at temperatures as warm as –10 °C (Koenig 1963; and Bruintjes et al., 1987). The Rosenfeld and Woodley measurements did not indicate whether ice coexisted with the supercooled water in these cold regions, and it has been known for some time that severe thunderstorms can contain supercooled water at cold temperatures. These results highlight one of the major uncertainties in glaciogenic seeding: What is the origin of ice in fresh updrafts? At a minimum the height and temperature of freezing depend on the vigor and isolation of the updrafts and the nature and quantity of the ice-forming nuclei. The CCN input into the clouds is another major determinant of ice in updrafts. Clouds with CCN concentrations of 100 cm^{-3} to 200 cm^{-3} readily develop raindrops through coalescence that freeze at temperatures of –10°C or warmer, even in updraft regions. If greater concentrations exist, however, coalescence will be suppressed and freezing will take place at much colder temperatures. This effect has been simulated with an explicit microphysics cloud model (Khain et al., 2001).

In conclusion, glaciogenic seeding has produced clear proof of microphysical changes to simple cloud systems, with indications based on statistical results that precipitation has been increased in some experiments. However, against the background of more than half a century of experimentation, many questions still remain and progress has been frustratingly slow due to limitations in understanding of the complex physical processes involved, insufficient design of some experiments, and at times, political, scientific, and funding pressures. There are still a number of issues that need to be addressed, including

- the transferability of results from simple cloud systems to larger, more complex storm systems that contribute significantly to area-wide precipitation;
- the link between the formation of ice in strong updrafts in regions of high supercooled liquid water and the development of larger graupel particles that could deplete the liquid water;
- the links between recently observed high concentrations of ice crystals, additional ice crystals produced by seeding, and their initial growth to more precipitation on the ground;
- the interactions between cloud dynamics and microphysics and how they may change due to seeding; and
- the measurement limitations of conventional radar.

Hygroscopic Seeding Experiments

Since its inception the term "hygroscopic seeding" has taken on slightly different meanings depending on the experimental design, type of seeding material used, and the type of cloud subject to experimentation. In all instances the ultimate goal has been to enhance rainfall by somehow promoting the coalescence process. The direct introduction of appropriately sized salt particles or droplets that can act as artificial raindrop embryos, using either water sprays, diluted saline solutions, or ground salts, are the most common hygroscopic seeding techniques that have been used (Biswas and Dennis, 1971; Czys and Bruintjes, 1994; Murty et al., 2000). The primary objective of introducing artificial raindrop embryos (such as salt particles larger than 10 μm dry diameter) is to short-circuit the action of the CCN population in determining the initial character of the cloud droplet population, and thus jump-start the coalescence process. This concept has been used in programs in the United States and other countries (Biswas and Dennis, 1971; Bowen, 1952; Cotton, 1982), and is still widely used in Southeast Asian countries. In fact, the India and Thai experiments reported statistically significant (α=0.05) increases in rain (Murty et al., 2000; Silverman and Sukarnjanasat, 2000). Despite this wide use the results are inconclusive due to the lack of physical understanding of the statistical results. Observations and modeling results have lent some support that under certain conditions with an optimal seed-drop (artificial embryos, see Rokicki and Young, 1978; Tzivion et al., 1994) size spectrum, precipitation could be enhanced in some clouds.

A recent development related to mixed-phase convective clouds is the use of hygroscopic flares. The flares produce small (mean dry diameter 0.5 μm to 1 μm) hygroscopic particles with a fairly long tail in the distribution toward larger sizes. The flares are used for seeding in the updraft areas below the bases of convective storms. Due to size and chemical characteristics, the hygroscopic particles have an advantage, compared to naturally occurring particles (especially continental CCN), in competing for available water vapor to activate cloud droplets, broadening the cloud droplet size distribution, and initiate condensation growth, thereby improving the efficiency of the rainfall formation process (Mather et al., 1997; WMO, 2000).

In both South Africa (Mather et al., 1997) and Mexico (WMO, 2000), hygroscopic flares were applied to mixed-phase convective cloud systems in physical-statistical experiments (i.e., statistical randomized seeding experiments with concurrent physical measurements). Aircraft microphysical measurements were made to verify some of the processes involved. Radar-measured 30 dBZ volumes produced by the convective complexes were tracked by automated software and various storm and track properties were calculated. These two sets of experiments produced remarkably similar results in terms of the difference in radar-estimated rainfall between the seeded and non-seeded groups (see Figure 2.3). The South African data have been reevaluated independently by Bigg (1997) and Silverman (2000), and both concluded that there is statistically significant evidence of an increase in radar-estimated rainfall from seeded convective cloud systems. For instance, Silverman's (2000) re-evaluation showed an increase in rain mass in the 30–60 minutes after seeding, significant at the 96 percent level (α=0.04) or higher.

The individual storms selected for the experiment, almost without exception, extended well above the freezing level. In the exploratory analyses done on the South African data (Mather et al., 1997), marked differences were found in storm properties above 6 km. The 6 km level generally corresponds to the –5°C to –10°C level and therefore points to probable ice-phase processes being part of the apparent seeding effect. Some indication of how the microphysical changes of broadening the droplet spectrum can be brought about by hygroscopic flare particles as well as supporting measurements are given by Cooper et al. (1997). Although these effects on the ice processes are not well understood and need further research, the following constitute continued progress:

- The natural contrast of high concentrations of ice particles in maritime clouds (in which collision and coalescence are active) that extend above the freezing level (Cotton, 1972; Koenig, 1963; Koenig and Murray, 1976; Scott and Hobbs, 1977), compared to the relatively low concentrations of ice particles found in continental clouds (in which coalescence is not active);
- The freezing temperature that increases with an increase in droplet size due to the higher probability that larger droplets will contain or come in contact with ice nuclei and the associated riming characteristics (Johnson, 1987); and
- The various ice-multiplication processes, including mechanical fracturing of fragile ice crystals during melting and evaporation, ice splinter formation during riming due to the pressure break-up of accreted drops, which are dependent on the presence of relatively large cloud droplets (> 24 μm) (Hallet and Mossop, 1974).

In the South African and Mexican hygroscopic flare experiments on mixed-phase clouds, the Thailand experiment using larger hygroscopic particles on exclusively warm clouds (Silverman and Sukarnjanasat, 2000), and the glaciogenic seeding experiment in Thailand (Woodley et al., 2003a,b), a delayed seeding response in radar-derived storm properties was observed. The South African and Mexican results were analyzed for the first hour after seeding, and the seeding effect was evident 20–60 minutes after seeding based on the statistical results. In the Thai hygroscopic and glaciogenic seeding experiments the seeding effects were evident only after a few hours. This result has been explained through some seeding-induced dynamic mechanism (Bigg, 1997; Mather et al., 1997; Silverman, 2000). The atmospheric kinematic structure and stability in the three experimental areas differs substantially, complicating the understanding of these apparent dynamic responses. Although some possible explanations have been suggested (Bigg, 1997), this is an issue that demands further investigation and proof.

As a result of the outcome of the hygroscopic seeding experiments, the WMO Executive Council in May 1999 convened a Working Group on Physics and Chemistry of Clouds and Weather Modification to review those activities, and subsequently (in collaboration with the National Center for Atmospheric Research in the United States and the State of Durango in Mexico) the council organized a workshop on hygroscopic seeding, held in Mazatlan, Mexico, in December 1999 (WMO, 2000).

The Mazatlan workshop reviewed the three recent randomized precipitation projects (South Africa, Mexico, and Thailand), which had the following common elements: (1) seeding with hygroscopic particles; (2) evaluation using a time-resolved estimate of storm rainfall based on radar measurements in conjunction with an objective software package for tracking individual storms; (3) statistical analyses indicating increases in radar-estimated rainfall; and (4) the necessity to invoke seeding-induced dynamic effects to explain the results. While the randomized seeding results were viewed as exciting, the workshop participants concluded that the chain of physical events is not well understood. It is generally accepted that this "second pillar" of scientific understanding is needed to reinforce the statistical results before such results can be fully accepted. The workshop participants also recommended that a major cooperative field experiment employing modern instrumentation be planned and carried out in the near future (WMO, 2000).

> The workshop concluded:
> The recent hygroscopic seeding experiments, if validated, lead beyond the classical result in cloud physics that links cloud condensation nuclei and droplet spectra at cloud base to the efficiency of rain (for example, the probability that a cloud of a given depth will produce rain). Rather, these experiments suggest that CCN affect the total rainfall from a cloud, and apparently also the longevity of the cloud. This result would have important practical implications not only for water resource needs but also for quantitative precipitation forecasting and for global change issues (for instance, interactions among regional temperature changes, changes in natural CCN concentrations, and precipitation patterns) (WMO, 2000).

As discussed in Chapter 2, recent satellite measurements have indicated that plumes of smoke from biomass burning and other sources inhibit coalescence and rain formation, and that salt dust (Rudich et al., 2002) and sea spray (Rosenfeld et al., 2002) enhance coalescence and precipitation in clouds in which the precipitation was otherwise suppressed due to the air pollution. This information, together with the results from the hygroscopic seeding experiments, suggests an intriguing idea that hygroscopic seeding could be used to override damaging, inadvertent seeding effects that inhibit rainfall, with more beneficial, deliberate seeding effects that enhance rainfall. This potential should be explored further.

CURRENT STATUS

During the last 10 years there has been thorough scrutiny and evaluation of projects involving glaciogenic seeding experiments. Although there are indications that seeding can increase precipitation based on the statistical results, a number of recent studies have posed new questions about these experiments. As a result, skepticism remains as to whether this method provides a cost-effective means for increasing precipitation for water resources. Common weaknesses of nearly all glaciogenic seeding experiments are the incomplete documentation of the physical chain of events and cause and effect relationships, and the incomplete understanding of the physical processes thought to be operating to increase the rainfall and to explain the oftentimes positive statistical results. An exception is orographic snowpack enhancement, for which many of the physical processes and causes and effects are better understood.

Although the dynamic seeding conceptual model is plausible and provides a logical chain of events to enhance precipitation, it is a very complex model, and many links in the chain are difficult to measure. Especially elusive has been the effect of seeding on downdrafts and the role this may play in communicating cloud-scale seeding effects to an area-wide effect. Focused observational experiments, modeling studies, and modern statistical evaluations (Appendix B) are needed to validate and support this hypothesis. Although rainfall increases from individual clouds on a limited scale have been documented, significant evidence of effects on areal rainfall patterns has not. It is these effects—not the area average or point measurements of rainfall—that are important.

Over mountainous terrain the timely identification of regions of supercooled liquid water and the efficient targeting and dispersing of seeding material remain difficult problems. These clouds are part of major winter cyclonic storms, which often have continuously changing wind flow regimes and cloud structures. Major uncertainties include the identification of the right cloud at the right time, the response time for delivering seeding material, the coverage on release, and the potential for volume filling. Evidence from plume tracking and measurement of seeding chemicals in fallen snow shows that plumes of seeding material often do not fill and catalyze the intended cloud volume (Reynolds, 1988; Stone and Warburton, 1989). Focused numerical modeling studies on the questions raised by targeting supercooled or liquid water in mountainous terrain can advance the understanding of seeding effects (Orville, 1996). Simultaneous use of the most advanced observing tools (described in Chapter 4) and improved statistical evaluation techniques will improve the success of such studies significantly.

Additional weaknesses in some experiments have been problems with the seeding devices and poor seeding execution. Grouping of all the days during the analysis phase and including some classes of clouds that should not be responsive to seeding may dilute the apparent effect of seeding. In addition, the large natural and experimental variability inherent in seeding convective clouds has made detection of a seeding signal very difficult. Finally, cuts in funding often have resulted in project termination well before any definitive result could reasonably have been expected.

To fully evaluate the utility of glaciogenic cloud-seeding agents requires a more complete understanding of natural ice formation processes. Measurements are needed of the origin of natural ice nuclei, what their composition is, how they act in clouds, and how they are distributed in the atmosphere. The impacts of changes and variability in engineered and natural aerosols on ice formation must also be investigated, so that their impacts on cloud modification efforts can be understood and even anticipated.

Pitfalls that have affected experiments in the past include errors in the statistical design and conceptual model, changes in seeding strategy or seeding material, inappropriate statistical or evaluation methods, and inadequate tools to conduct the experiment. Statistical experimental design, including the sample size and length of the experiment, must be appropriate in order to detect the statistical significance of changes that occur in response to seeding (Fletcher and Steffens, 1996; Gabriel, 1999, 2000; Mielke et al., 1984; Ryan and King, 1997; Smith et al., 1984). However, appropriate experiments are difficult to design according to the "classical" perspective, because there can never be a true control; the atmosphere is dynamic and constantly changing. A detailed review of the evaluation of weather modification experiments and current statistical methods is given in Chapter 3 and Appendix B.

While the classical (i.e., large particle salt powders) warm cloud-seeding technique is still widely used in countries in Southeast Asia, statistical experiments have shown mixed results. Observations and modeling results have lent some support that under certain conditions with an optimal seed drop-size spectrum (Rokicki and Young, 1978; Tzivion et al., 1994), precipitation could be enhanced in some clouds. Disadvantages of this approach are that large quantities of salt are needed and dispersion of the salt into the cloud inflow is difficult to accomplish. In addition, the growth rates of the particles to raindrops must match the updraft profile or their growth will be inefficient (Klazura and Todd, 1978; Young, 1996). In a modeling study Farley and Chen (1975) found that salt seeding only produced a few large drops without a significant effect on the precipitation process unless drop breakup acted to induce a chain reaction that enhanced the effects of seeding. While some positive effects have been reported (Biswas and Dennis, 1971; Murty et al., 2000; Silverman and Sukarnjanasat, 2000), seeding with hygroscopic material has usually appeared less attractive than seeding with ice nuclei due to the lack of physical understanding.

Although promising statistical results have been obtained with hygroscopic seeding, some fundamental questions regarding the physical processes need to be answered in order to provide a sound scientific basis for this technology. The physical processes responsible for the apparent successes in South Africa and Mexico using small hygroscopic particles are not fully understood.

One fundamental impediment is the diffusion and transport of seeding material throughout the cloud. Weil et al. (1993) showed that it takes more than 10 minutes for a plume released in a cloud to spread over distances of several kilometers and to fill an updraft region of a single cell. It has been hypothesized that the initial spreading of seeding effects through a cloud occurs via the formation of drizzle drops. A possible solution to this problem is to seed only the strongest updrafts, which are expected to rise to near cloud top, where any drizzle-size drops produced might spread and be carried downward in the descending flow near the cloud edge. According to Blyth et al. (1988) such material would spread throughout the cloud and might affect large regions of the original turret and perhaps other turrets. Such a circulation is supported by the observations of Stith et al. (1986, 1990, 1996).

A modeling study by Cooper et al. (1997) indicated that the concentrations of drizzle drops produced by seeding can vary by several orders of magnitude, depending on the size spectra of seed particles. Reisin et al. (1996), Yin et al. (2000a,b), and Caro et al. (2002) found similar results and suggested that for seeding to have an optimum effect (producing sufficient concentrations of drizzle-size drops), mean seed particle radii between 0.5 μm and 6 μm are needed. These modeling studies indicate that the role of background CCN and giant CCN is crucial for determining the effectiveness of the seeded particles, because the seeded nuclei compete with background aerosols for the available water vapor. The results from these model calculations should be interpreted with considerable caution, because they oversimplify the precipitation formation process and the complex dynamics of convective clouds.

In addition, the suggested dynamic effects need to be explored further, and the modeling studies need to be validated by observations. In summary, while some recent experiments provided good statistical results, there are nonetheless many uncertainties with respect to the physical interpretation of the statistical results that remain to be addressed. Some of the most critical of these uncertainties are summarized in Box 2.2.

A more detailed understanding of the chain of events of microphysical and dynamical processes in clouds and their responses to hygroscopic and glaciogenic seeding is needed. The initial development of large drops in a cloud, the origin of ice in clouds, and liquid- and ice-phase interactions in the development of precipitation are not well understood.

A coupled cloud-dynamical response is apparent in many hygroscopic and glaciogenic cloud-seeding experiments; for instance, many experiments have indicated increases in rainfall beyond 30 minutes after treatment, which may be indicative of dynamic responses that were not anticipated in the original conceptual models. These interactions are not well understood.

There are uncertainties related to the use of radar alone to estimate rainfall. It is possible that some statistical results using radar-derived precipitation estimates might be due to seeding-induced drop size changes that affect the radar observations (Yin et al., 1998). Additional field measurements of raindrop spectra are needed to address this issue. Due to inherent assumptions of relating reflectivity from conventional weather radar to meteorological parameters, there are limitations on discriminating between the liquid water and ice phases and changes in the concentrations and sizes of precipitation particles. These are exactly the characteristics that are assumed to change by cloud seeding in mixed-phase clouds. Furthermore, conventional radars do not provide information on the complex motions in cloud systems, how these motions impact the microphysics and vice versa, or how these motion fields may be affected by seeding. New radar technologies and techniques (discussed in Chapter 4) and new statistical evaluation techniques (discussed in Appendix B) may help address these issues.

Most reported cloud-seeding results have come from single-cloud (or storm) experiments, which do not necessarily address the question of how area-wide precipitation may be affected by seeding. In addition, the results from a seeding experiment in one region cannot automatically be transferred to other geographic areas, since large-scale weather systems, topography, background aerosols, and the thermodynamic and wind profiles will affect the feasibility and impact of seeding in any particular location. To increase the likelihood of successful transferability all environmental conditions and methodology of seeding must be replicated (Cotton and Pielke, 1995), a skill far greater than currently available. Such issues must be examined for all applications of weather modification.

Related uncertainties pertain to the issue of “extra-area” effects, that is, whether seeding can affect the weather beyond the targeted temporal or spatial range. The persistent effects of cloud seeding claimed by Bigg (1995) should be carefully assessed, as should the statistical results from experiments in Thailand (Silverman and

Sukarnjanasat, 2000; Woodley et al., 2003b) and Israel (Brier et al., 1973), which claim effects beyond a few hours. Some argue that increasing precipitation in one region could reduce precipitation downwind (by "stealing" the atmospheric water vapor), or conversely, could enhance precipitation downwind (by increasing evaporation and transpiration and thus providing more moisture for clouds). Such claims, however, currently belong to the realm of speculation, as no quantitative studies of this issue have been conducted. This is a challenging issue to address, due to the current limitations of quantitative precipitation forecasting.

The need to predict what would have happened had there been no weather modification (which is especially important in the context of attempts to modify hazardous weather) places an enormous burden on prediction. Predictive numerical models are required to accurately assess what would have occurred in the absence of any intervention, in order to assess both the magnitude and the potential consequences of the change. However, model development and physical understanding are interdependent, thus advances in both are slow and iterative.

The progress in these areas, together with new observational, laboratory, and modeling tools (discussed in Chapter 4), substantially enhances our capabilities to address the issue of weather modification with renewed vigor. The biggest challenge facing the community is to bring more modern technology to bear in addressing the outstanding uncertainties discussed in this chapter.

Given the number of operational programs worldwide there is clearly a perceived need for deliberate weather modification to enhance precipitation and to mitigate some forms of severe weather. At this time scientific knowledge badly lags the perceived need. Without a systematic research effort organized to address the most pressing scientific uncertainties, this gap is certain to widen. The water resources and land-use sectors should be integral parts of such a research effort. Transforming cloud-seeding information and results into a geographical information system format could, for example, facilitate cooperation between meteorological, water resources, and land-use specialists. Viable precipitation enhancement techniques remain an attractive and economical prospect, and they deserve focused attention and long-term support. The development of a stable funding environment to develop a new generation of scientists working in this field is needed.

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B

Modern Statistical Methods and Weather Modification Research[1]

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INTRODUCTION

As discussed in the report, statistical science is important in the design, analysis, and verification of weather modification experiments. Given the complexity of the problem, the necessity to include statisticians in the planning and analysis of such experiments was recognized early in the history of weather modification. Indeed, many excellent and well-known statisticians have collaborated on such experiments over the years. In addition to improvements in deterministic modeling, fundamental science, and technology, there have been tremendous strides in the statistical sciences over the past two decades as well. Given the importance of statistics to weather modification experiments, this is indeed a significant and relevant development.

The aforementioned revolution in statistical methodology and computation has led to many new perspectives that were not available in past weather modification research programs. For example, one will never be able to "randomize" effectively all sources of uncontrollable bias in weather modification experiments. Consequently, sophisticated statistical models have to be considered to explore potential significant effects. That is, one can now compare "treatment'" and "control" environments from a spatio-temporal perspective, rather than some potentially inappropriate summary over space/time/variate. Complicated (realistic) spatio-temporal statistical methodologies were either not available or could not be implemented in realistic settings until the 1990s. A simple analogy is that R. A. Fisher was aware of the effects of spatial dependence in nearby field plots in agricultural experiments. The computational and modeling technology did not exist at the time to adequately model such effects. Consequently, randomization was utilized to mitigate the effects of spatial correlation. However, just as blocking designs can improve efficiency over randomization, one can get more efficient estimates by modeling the spatial (and spatio-temporal) effects (e.g., see Cressie, 1993).

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[1] This appendix was added by request of the Committee to supplement the statistical discussion in the main body of the report.

Statistical modeling theory has advanced significantly since the last major weather modification initiative. In particular, in addition to advancements in spatial and spatio-temporal approaches, methodologies such as generalized additive models and generalized linear mixed models have proven to be quite powerful, and relevant. For example, the generalized linear mixed model framework allows for a broad class of data distributions (i.e., one is not restricted to normality) and considers some function of the expected mean response to be the sum of a deterministic (i.e., regression) component and a (correlated) random component, if needed. Thus, in addition to known covariate effects in the deterministic component, unknown spatial, temporal or spatio-temporal effects can be considered explicitly as the random effects in this framework. This is critical as discussed above since weather modification experiments occur over space and time. Thus, this framework provides a natural way to incorporate the advancements in spatial statistics within a broader model-based analysis. Estimation for these models is performed by relatively computer intensive approximate numerical procedures. For an overview see McCulloch and Searle (2001).

Perhaps an even more "revolutionary" development in statistics was the realization that Markov Chain Monte Carlo (MCMC) methods could be used to implement Bayesian statistical models. Inspired by the use of such methods in image analysis by Geman and Geman (1984), Gelfand and Smith (1990) realized that MCMC can be used as a general approach in which to implement Bayesian statistical models. This led to a dramatic increase in the types and complexity of problems that can be modeled in this context. For an overview of the approach see Robert and Casella (1999). This development is critical to the science of weather modification for a couple of reasons. First, the Bayesian paradigm provides a natural statistical framework in which to explicitly account for ALL sources of uncertainty, be they data, model, or parameter uncertainties (e.g., Berliner 1996). Second, such models can be used to incorporate very complicated spatial and temporal dependence in the generalized linear mixed model framework discussed above with relative ease (e.g., Diggle et al., 1998). Furthermore, one can include complicated physical insight (i.e., model physics) directly into this framework (Wikle et al., 2001). This methodology is outlined in greater detail in the following section.

HIERARCHICAL BAYESIAN MODELS

The use of Bayesian ideas in weather modification is not new (e.g., see Olsen 1975), yet such ideas have not entered the mainstream of weather modification research. This is unfortunate, as the Bayesian paradigm is ideal for combining different sources of information (e.g., physics and data) and accounting for uncertainty. Common meteorological procedures such as found in data assimilation have long been recognized as inherently Bayesian in nature (e.g., Lorenc and Hammon, 1988). In addition, it has recently been recognized that one of the fundamental approaches to characterizing uncertainty in climate change assessment is Bayesian (e.g., Berliner et al. 2000; Leroy 1998). However, traditionally it has been difficult to model the full data, process, parameter distributions in general from the Bayesian perspective. Recently, it has been shown that hierarchical approaches to such models provide an ideal framework in which to account for all such uncertainties in geophysical processes (e.g., Royle et al., 1999; Wikle et al., 2001).

The hierarchical Bayesian statistical paradigm is based in probability theory (e.g., Berger, 1985; Bernardo and Smith, 1994). Assume we are interested in some process Y and we have observational data for this process, denoted by z. Furthermore, there are parameters associated with our physical-statistical representation of the Y process, as well as the statistical model for the observations. The collection of these parameters is denoted by θ. A Bayesian hierarchical analysis develops a joint probability model for all these variables as the product of a sequence of distributions; formally,

$$[z, Y, \theta] = [z \mid Y, \theta][Y \mid \theta][\theta], \tag{1}$$

where the brackets [ ] denote probability distribution and vertical bars | identify conditional dependencies for a given process upon other processes and/or parameters. For example, $[z \mid Y, \theta]$ denotes the distribution of the data z conditional on the process Y and parameters θ. The process distribution is then given by $[Y \mid \theta]$ and the parameter distribution by $[\theta]$. Learning about the unknown quantities of interest (e.g., Y and θ) relies on the probability relationship (Bayes's Theorem):

$$[Y, \theta \mid z] \propto [z \mid Y, \theta][Y \mid \theta][\theta], \tag{2}$$

where the constant of proportionality arises by integrating the right-hand side of (2) with respect to Y and θ.

We can make use of physical relationships to aid in the specifications of the "prior distributions" $[Y \mid \theta]$ and $[\theta]$. Our ultimate interest is with the left-hand side (LHS) of (2), the so-called "posterior distribution." This distribution of the process and parameters given the data updates the prior formulations in light of the observed data. For instance, as shown by Royle et al. (1999), if the process consists of winds u, v, and pressure P, we can exploit the geostrophic relationship, which would allow us to write a stochastic model for the wind field given the pressure field, $[u, v \mid P, \theta]$. Note that this is a stochastic relationship (i.e., a distribution), which quantifies a source of variability with respect to deviations from the gradient relationship (e.g., $u \propto \partial P / \partial y, v \propto \partial P / \partial x$). We can model additional uncertainty by specifying distributions for the parameters θ as well. For example, the geostrophic model suggests a parameter (to be included as an element of the vector θ) that is proportional to the inverse product of the density times the Coriolis term. One might specify this as the prior expected value. A variance about this expected value is then prescribed to generate a distribution for this parameter. The net result is that with relatively simple physical and stochastic representations in the sequence of conditional models (e.g., RHS of [2]), we can obtain a posterior distribution for u and v that has very complicated spatial structure; one that, through the quantification of uncertainty, can "adapt" to a wide variety of observations and our prior knowledge of the geophysical system.

Each stage of the hierarchical model (i.e., data, process, and parameter stages) can be further partitioned into subcomponents. This is critical in that it allows for inclusion of many complications that are extremely difficult to account for in traditional statistical implementations. Each stage is further discussed below.

Data Models

Datasets commonly considered for atmospheric processes are complicated and usually exhibit substantial spatial, temporal, or spatio-temporal dependence. The major advantage of modeling the conditional distribution of the data given the true process is that substantial simplifications in model form are possible. For example, let z_a be data observed for some process Y, and let θ_a be parameters. The data model is written, $[z_a \mid Y, \theta_a]$. Usually, this conditional distribution is much simpler than the unconditional distribution of $[z_a]$ since most of the complicated structure comes from the process Y. Often, this model simply represents measurement error. Note that in this general framework the measurement error need not be additive. Furthermore, and perhaps more importantly, this framework can also accommodate data that is at a different resolution in space and/or time than the process.

This framework also provides a natural way to combine datasets. For example, assume that z_a and z_c represent data from two different sources (e.g., rain gauge and radar measurements of precipitation). Again, let Y be the process of interest (e.g., the true precipitation process) and θ_a, θ_c be parameters. In this case, the data model is often written

$$[z_a, z_c \mid Y, \theta_a, \theta_c] = [z_a \mid Y, \theta_a][z_c \mid Y, \theta_c]. \tag{3}$$

Thus, conditioned on the true process, the data are assumed to be independent. Of course, this does not suggest that the two datasets are unconditionally independent. Rather, the majority of the dependence among the datasets is due to the process, Y. This assumption of independence is exactly that, an assumption. Although often very reasonable, it must be assessed critically for each problem.

The conditional partitioning of the datasets in (3) is often similarly applied to multivariate models. That is, say our processes of interest are denoted Y_a and Y_c, with associated observations z_a and z_c. One might write

$$[z_a, z_c \mid Y_a, Y_c, \theta_a, \theta_c] = [z_a \mid Y_a, \theta_a][z_c \mid Y_c, \theta_c]. \tag{4}$$

Again, this represents the assumption that given the true processes of interest, the datasets are independent. Such an assumption must be evaluated and is not required in hierarchical analysis, but it is often very reasonable and can lead to dramatic simplifications in the computations.

Process Models

It is usually the case that developing the process distribution is the most critical step in constructing the hierarchical model. This distribution is often further factored hierarchically into a series of submodels. For example, assume the process of interest is composed of two subprocesses, Y_a and Y_c. Perhaps Y_a represents precipitation for a geographical region and Y_c might represent the state of the atmospheric circulation over the same region. Furthermore, define parameters $\theta_Y = \{\theta_{Y_a}, \theta_{Y_c}\}$ that describe these two processes. One might consider the decomposition,

$$[Y_a, Y_c \mid \theta_Y] = [Y_a \mid Y_c, \theta_Y][Y_c \mid \theta_Y]. \tag{5}$$

This is just a fact of probability theory and can always be written. However, it may be the case that one can assume the parameters are conditionally independent in which case the right hand side of (5) can be written as $[Y_a \mid Y_c, \theta_{Y_a}][Y_c \mid \theta_{Y_c}]$. The challenge is the specification of these component distributions. Indeed, most of the effort in the development of hierarchical models is related to constructing these distributions. It is often the case, however, that there is very good scientific insight that can suggest appropriate conditioning order and possible models for the component distributions. For example, it is probably more reasonable to condition precipitation on the atmospheric circulation state variables, rather than the alternative. Similarly, Y_a might represent the process of interest at time t and Y_c the same process at the previous time, $t-1$. Natural deterministic models for process evolution could suggest the form of such models.

Parameter Models

The parameter distributions may require significant modeling effort. As is the case with the data and process models, the joint distribution of parameters is often partitioned into a product of marginal distributions. For example, consider the data model (4) and process model (5). One must specify the parameter distribution $[\theta_a, \theta_c, \theta_{Y_a}, \theta_{Y_c}]$. Often, one can make reasonable independence assumptions regarding this distribution, e.g., $[\theta_a, \theta_c, \theta_{Y_a}, \theta_{Y_c}] = [\theta_a][\theta_c][\theta_{Y_a}][\theta_{Y_c}]$. Of course, this assumption must be justified. There are usually appropriate submodels for parameters as well, leading to other levels of the model hierarchy. In many cases, for complicated processes, there is substantial scientific insight that can go into developing the parameter models (e.g., Wikle et al., 2001). In other cases, one does not know much about the parameter distribution, suggesting “vague priors” or data-based estimates be used. That is, it is often useful to think empirically at first and perform exploratory data analysis in order to develop understanding about the process. The emphasis in this case is on model building.

The development of parameter distributions has often been the focus of objections due to its implied subjectiveness. Of course, the formulation of the data and process models are quite subjective as well, but those choices have not generated as much concern, probably because such subjectiveness is just as much a part of classical model building as it is the Bayesian approach. One must recognize that a strength of the hierarchical (Bayesian) approach is the quantification of such subjective judgment. Hierarchical models provide a coherent probabilistic framework in which to incorporate explicitly in the model the uncertainty related to judgment, scientific reasoning, subjective decisions, and experience.

EXPERIMENTAL DESIGN

As indicated in the report, the proper statistical design of weather modification experiments is paramount. Advances in statistical modeling, some of which were outlined above, should be considered in this aspect of the problem as well. For example, there has been a significant amount of work considering the design of efficient monitoring networks in cases where the underlying process of interest is spatial. A nice recent review of such work can be found in Muller (2000). In addition, in the context of spatio-temporal processes, work has been done to consider how one might gain efficiency by allowing monitoring networks to be dynamic in time (e.g., Wikle and Royle, 1999). Finally, there has been recent work related to utilizing the advantages of the Bayesian paradigm in the context of experimental design (e.g., Besag and Higdon, 1999). Weather modification research could benefit from these advances. For example, experimental data from past weather modification experiments could be used to develop understanding of spatio-temporal dependencies in the atmospheric variables and constituents of interest. This understanding (prior knowledge) could then be expressed formally in terms of a statistical model. At that point, one could utilize a decision theoretic framework to optimize specific objectives. For example, one might be interested in determining the optimal location for rain gauges in order to maximize the ability to detect a significant difference in seeded precipitation over a given spatial region. It may be, in this example, that such a network would be optimized by allowing some monitors to be fixed and others to vary location at different times, depending on the underlying dynamical environment. The underlying framework presented here would suggest the optimal locations for such monitors. In each phase of this analysis, modern model-based statistical methods could be used. Although such a model-based design perspective is advantageous, one could still use the model building and data analysis approach suggested here to analyze results from past experiments or from new experiments that were not designed from this perspective.

CONCLUSION

In addition to new technological advances in the atmospheric sciences, substantial advances also have occurred in the statistical sciences over the past three decades. These developments—which have not yet been applied to weather modification—could greatly improve the design, analysis, and verification of experiments. With the appropriate combination of statistical, computational, and scientific advances, many of the uncertainties in establishing the validity of weather modification research and operational results could be diminished.

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C

Glossary

These definitions were generated and modified by the Committee and report reviewers and from the American Meteorological Society glossary, 2nd edition (2000); the latter are denoted with an asterisk (*).

***Accretion:** In cloud physics, the growth of an ice *hydrometeor* by collision with supercooled cloud drops that freeze wholly or partially upon contact.

Aerosol: Suspension of solid or liquid particles in air or gas (as smoke, fog, or mist).

***Anthropogenic:** Human-induced or resulting from human activities.

Bin models: Cloud models in which the size distribution of particles is specified over discrete intervals (bins).

Blocking (or block design experimentation): Separating experimental units that are known before the experiment to be similar in some way (e.g., the same type of cloud in two different locations, say the windward and leeward side of a mountain, where each location is considered a block); *randomization* of experiments then is carried out in each block. Blocks restrict randomization by accounting for important outside variables (e.g., location) by incorporating those variables into the experimental design.

Cloud condensation nuclei (CCN): Particles, either liquid or solid, upon which water vapor condenses and forms cloud drops in the atmosphere.

Cloud liquid water: The amount of non-precipitating liquid water in a cloud, usually measured in gm^{-3}.

*** Cloud seeding:** The introduction of agents into a cloud to alter the phase and size distribution of cloud particles for the purpose of modifying its development or increasing its precipitation. The most frequently used agents are silver iodide, granulated solid carbon dioxide (dry ice), and salt.

* **Coalescence:** In cloud physics, the merging of two water drops into a single larger drop after collision.

* **Cold (supercooled) cloud:** A cloud composed of *supercooled water* drops.

* **Condensation:** The physical process by which a vapor becomes a liquid; the opposite of evaporation.

Covariates: Measurement of two or more variables against each other over time to see how they vary together.

Cross-over: A technique in which the same site is used alternately in a randomized scheme both for experimentation and control to minimize location-specific bias.

Deposition: The physical process that occurs in subfreezing air when water vapor changes directly to an ice without becoming a liquid first; the opposite of sublimation.

Double-blind: A type of experiment in which neither the experimenters nor the evaluators know which subjects were treated; this is done to remove all human bias in evaluation. Specifically in weather modification, both the experimenters and the evaluators are unaware of which clouds are being seeded until after the experiment is completed and the results have been evaluated.

Dynamic seeding: Seeding to increase a cloud's potential for rainfall by causing it to grow larger and last longer than it would have grown without seeding. Transformation of water droplets to ice crystals is sought to release the latent heat of fusion to enhance buoyancy and invigorate cloud growth.

Glaciogenic seeding: Process of enhancing ice content in clouds either by nucleating new crystals or freezing cloud droplets.

Ground generators: In weather modification, usually refers to silver iodide smoke generators that are operated from the ground (as opposed to airborne equipment).

* **Graupel:** Heavily *rimed* snow particles, often called snow pellets.

Homogeneous nucleation: Nucleation that occurs without the intervention of a pre-existing foreign particle.

* **Hydrometeor:** Any product of *condensation* or *deposition* of atmospheric water vapor, whether formed in the free atmosphere or at the Earth's surface; also, any water particle blown by wind from the Earth's surface.

Hygroscopic: The ability of condensation nuclei to absorb water and thus to accelerate the *condensation* of water vapor.

Hygroscopic seeding: Process of enhancing water droplet size distribution in clouds by introducing hygroscopic nuclei with the objective of rain enhancement or hail suppression.

Mixed-phase cloud: A cloud in which ice particles are intermingled with *supercooled water* drops.

* **Negative cloud-to-ground lightning:** A lightning flash or stroke between a cloud and the ground that lowers a negative charge to the ground.

* **Nowcast:** A short-term weather forecast, generally for the next few hours.

* **Nucleation:** The initiation of a phase change of a substance to a lower themodynamic energy state (i.e., vapor to liquid *condensation,* vapor to solid *deposition,* or liquid to solid freezing).

Nuclei: A particle of any nature upon which, or the location at which, molecules of water or ice accumulate as a result of a phase change to a more condensed state; an agent of *nucleation*.

Null hypothesis: The statement being tested in a test of significance, which is designed to assess the strength of evidence of a claim; the null hypothesis often is the reverse of what the experimenter believes, put forth to be contradicted by the data.

Orographic cloud: A cloud whose form and extent is determined by the disturbing effects of orography (i.e., mountains), which causes lifting and condensation in the passing flow of air. Because these clouds are linked to the terrestrial relief, their location changes very slowly, if at all.

Overseeding: Condition in a cloud where an excess of nuclei are available, thereby creating a competition for the available cloud droplets or water vapor, possibly preventing any of them from growing to the appropriate size necessary to reach the ground.

* **Positive cloud-to-ground lightning:** A lightning flash or stroke between a cloud and the ground that lowers a positive charge to the ground.

Pre-screening: The removal of some weather or cloud conditions for consideration in the design of an experiment before randomization on the balance is made. This is done to focus the experiment on the conditions of interest.

Randomization: The use of chance to determine experimental units to minimize the sources of bias on the results. Specifically in weather modification, the design of experiments by dictating that, for example, “seed” or “don’t seed” decisions be made purely randomly.

Replication: Repeating each experiment on a large enough number of subjects to allow the systematic effects of the experiments to be seen; it reduces the role of chance variation and makes the experiment more sensitive to differences among experiments.

Re-randomization: Also known as resampling or Monte-Carlo tests, it is the construction of artificial datasets using a collection of real data on which experiments are rerun with seed and no-seed allocations selected at random. The percentage of such re-randomized seeding effects that exceed the actual real result is the probability of the real result occurring by chance.

Riming: The rapid freezing of *supercooled water* droplets as they impinge upon an exposed object and accrete to it.

Snowpack: The amount of annual accumulation of snow at higher elevations.

Static seeding: A strategy for optimum *nucleation*; exploiting the preexisting situation where less-than-optimal ice crystal concentrations exist, which leads to prolonged periods of supercooled water, with no attempt to modify the dynamics of the seeded clouds.
[alt.] Influencing precipitation formation processes by changing the microphysics of the cloud.

*** Supercooled water:** Liquid water at temperatures below the freezing point (0°C or 32°F).

Variance: A measure of the spread about the mean if the mean is a measure of the center of a group of observations; it is defined as the average of the squared deviations of a value from its mean. The variance also is the standard deviation squared.

Warm cloud: A cloud composed of liquid water drops at temperatures above the freezing point (0°C or 32°F).

D

Acronyms

ACWC	Advisory Committee on Weather Control
AMS	American Meteorological Society
ARM	Atmospheric Radiation Measurement program
BASC	Board on Atmospheric Sciences and Climate
CAPS	Cloud, Aerosol, and Precipitation Spectrometer
CART	Cloud And Radiation Test bed
CCN	Cloud Condensation Nuclei
CDS	Cloud Droplet Spectrometer
CG	Cloud-to-Ground (lightning)
CIP	Cloud Imaging Probe
CPI	Cloud Particle Imager
DOE	Department Of Energy
ETL	Environmental Technology Laboratory
FACE	Florida Area Cumulus Experiment
FN	Freezing Nuclei
FSSP	Forward Scattering Spectrometer Probe
GPM	Global Precipitation Mission
GPS	Global Positioning System
HIPLEX	High Plains Experiment
IN	Ice Nuclei
LWC	Liquid Water Content
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NWS	National Weather Service
OAP-260X	Optical Array Probe
SIP	Secondary Ice Particles
TITAN	Thunderstorm Identification Tracking Analysis and Nowcasting
TRMM	Tropical Rainfall Measuring Mission
WMO	World Meteorological Organization

E

Community Participation

The Committee would like to express its appreciation to following individuals for providing valuable insight and discussion throughout all phases of the report. The Committee especially acknowledges the assistance of Dr. Christopher Wikle who assessed the statistical aspect of the report and contributed an addendum (Appendix B) specifically discussing the application of modern statistical methods to weather modification.

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Terry Clarke, National Center for Atmospheric Research
Al Cooper, National Center for Atmospheric Research
Bill Cotton, Colorado State University
Shannon Cunniff, U.S. Bureau of Reclamations
Jim Dodge, National Aeronautics and Space Administration
Kelvin Droegemeier, University of Oklahoma
Kerry Emanuel, Massachusetts Institute of Technology
Brant Foote, National Center for Atmospheric Research
John Gaynor, National Oceanic and Atmospheric Administration
Lew Grant, Colorado State University
Robert Hirsch, U.S. Geological Survey
Edward Johnson, National Weather Service
Terry Krauss, Weather Modification, Inc.
Darin Langerud, North Dakota Atmospheric Resource Board
Jane Lee, Texas Department of Agriculture
Brooks Martner, National Oceanic and Atmospheric Administration/Environmental Technology Laboratory
Paul Mielke, Colorado State University
Jarvis Moyers, National Science Foundation
Harry Orville, South Dakota School of Mines
David Reynolds, National Weather Service, San Francisco Bay Area Office
Archie Ruiz, Active Influence & Scientific Management
Tommy Sherrer, Weather Modification Consultants
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F

Committee Member Biographies

Dr. Michael Garstang (Chair) is Distinguished Emeritus Research Professor in the Department of Environmental Sciences at the University of Virginia. He received his Ph.D. in meteorology from Florida State University. His research interests include convective storms, tropical marine and continental meteorology, trace gas and aerosol transports, and experimental meteorology. Dr. Garstang is a fellow of the American Meteorological Society (AMS). He has served on numerous committees, including the AMS Committee on Hurricanes and Tropical Meteorology and the AMS Committee on Planned and Inadvertent Weather Modification. He served as chief editor of *Journal of Applied Meteorology* from 1998 to 2003.

Dr. Roscoe R. Braham, Jr., is a professor and scholar-in-residence in the Department of Marine, Earth and Atmospheric Sciences at North Carolina State University. He received his Ph.D. from the University of Chicago and served on its meteorology faculty for 37 years. His research interests include cloud physics, thunderstorms, lake-effect snowstorms, and weather modification. He served as president of the American Meteorological Society (AMS) in 1988, and has received the Losey Award of the Institute of Aeronautical Sciences, the AMS's Rossby and C. F. Brooks Awards, the Department of Commerce Silver Medal, and the Weather Modification Association's Schaefer Award for scientific and technological discoveries that have constituted a major contribution to the advancement of weather modification. Dr. Braham is a fellow of the American Association for the Advancement of Science, the AMS, and the Royal Meteorological Society.

Dr. Roelof T. Bruintjes is a scientist in the Research Applications Program at the National Center for Atmospheric Research. He received his Ph.D. in physics from the University of South Africa. His research interests include precipitation enhancement and cloud processes. Dr. Bruintjes is a member of the American Meteorological Society (AMS) and is chairman of the AMS Committee on Planned and Inadvertent Weather Modification. He has served on the AMS Committee on Cloud Physics as well as the Executive Committee of the International Commission on Clouds and Precipitation (ICCP) of IAMAP in the IUGG from September 1992–2000. He is also an executive member and past president of the Weather Modification Association.

Dr. Steven F. Clifford is a research associate at the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder. He was formerly the director of NOAA's Environmental Technology Laboratory. He received his Ph.D. in engineering science from Dartmouth College. One of his research goals is to develop a global observing system using ground-based, airborne, and satellite-remote-sensing systems to better observe and monitor the global environment and use these observations as input to global air-sea circulation models for improving forecasts of weather and climate change. He was the recipient of the 1998 Meritorious Presidential Rank Award. He is a fellow of the Optical and Acoustical Societies of America, a senior member of the Institute of Electrical and Electronics Engineers, and a member of the American Physical Society, the American Geophysical Union, and the American Meteorological Society. He is also a member of the National Academy of Engineering and a member of the NRC's Board on Atmospheric Sciences and Climate.

Dr. Ross N. Hoffman is the vice president for Research and Development at Atmospheric and Environmental Research, Inc. Dr. Hoffman's principle areas of interest are objective analysis and assimilation methods, atmospheric dynamics, climate theory, and atmospheric radiation. He has made significant contributions in the field of data assimilation, including the development of some variational techniques. He is a member of the NASA Ocean Vector Wind Science Team and the Global Tropospheric Wind Sounder Science Definition Team. Dr. Hoffman received his Ph.D. in meteorology from the Massachusetts Institute of Technology

Dr. Douglas K. Lilly is a professor emeritus in the Department of Meteorology at the University of Oklahoma. He has recently been a Distinguished Senior Scientist at the National Severe Storms Laboratory conducting research related to tornadoes and other strong low-level vortices. His principal research interests have included the dynamics of convective clouds and storms, mountain waves and down-slope windstorms, two-dimensional and boundary-layer turbulence, cloud-topped mixed layers, and numerical simulation techniques. He has served as a senior scientist at the National Center for Atmospheric Research; director of the Cooperative Institute for Mesoscale Meteorological Studies, a NOAA-Oklahoma University joint institute; and director of the Center for Analysis and Prediction of Storms. He received the Rossby Medal from the American Meteorological Society and the Symons Memorial Medal from the Royal Meteorological Society. He is a member of the National Academy of Sciences.

Robert J. Serafin is Director Emeritus of the National Center for Atmospheric Research. He received his Ph.D. in Electrical Engineering from the Illinois Institute of Technology. His technical interests are related to radar, remote sensing, and in situ sensing of the atmosphere. He has expertise in the areas of signal processing theory, Doppler radar, lidar, and passive remote sensing techniques, and in the use of such systems for applications including severe weather detection, weather forecasting, precipitation estimation, and hydrological studies. Dr. Serafin is a member of the National Academy of Engineering and has served on many NRC committees, including the Space Studies Board, and as chair for both the Committee on Tools for Tracking CBN Releases in the Atmosphere and the Committee on National Weather Service Modernization. He is also a past president of the American Meteorological Society and current fellow, and a fellow of the Institute of Electrical and Electronics Engineers.

Dr. Paul D. Try is the senior vice president and program manager at Science and Technology Corporation (STC) and director of the International Global Energy and Water Cycle Experiment Project Office. He received his Ph.D. in atmospheric sciences from the University of Washington. Dr. Try has expertise in meteorological in situ and remote sensors (satellite and radar), as well as data collection, processing, exchange and archival activities. Before joining STC he served in the U.S. Air Force where he provided oversight management of all DOD research and development in environmental sciences. Dr. Try is a fellow of the American Meteorological Society and was its president in 1996-97.

Dr. Johannes Verlinde is an associate professor of meteorology at Pennsylvania State University. He received his Ph.D. in atmospheric science from Colorado State University. His research interests include the dynamical and microphysical processes in cloud, radar signal processing, and microphysical retrieval from remotely sensed measurements. Dr. Verlinde is a member of the American Meteorological Society (AMS) and the American Geophysical Union. He is currently serving on the AMS committee for cloud physics.

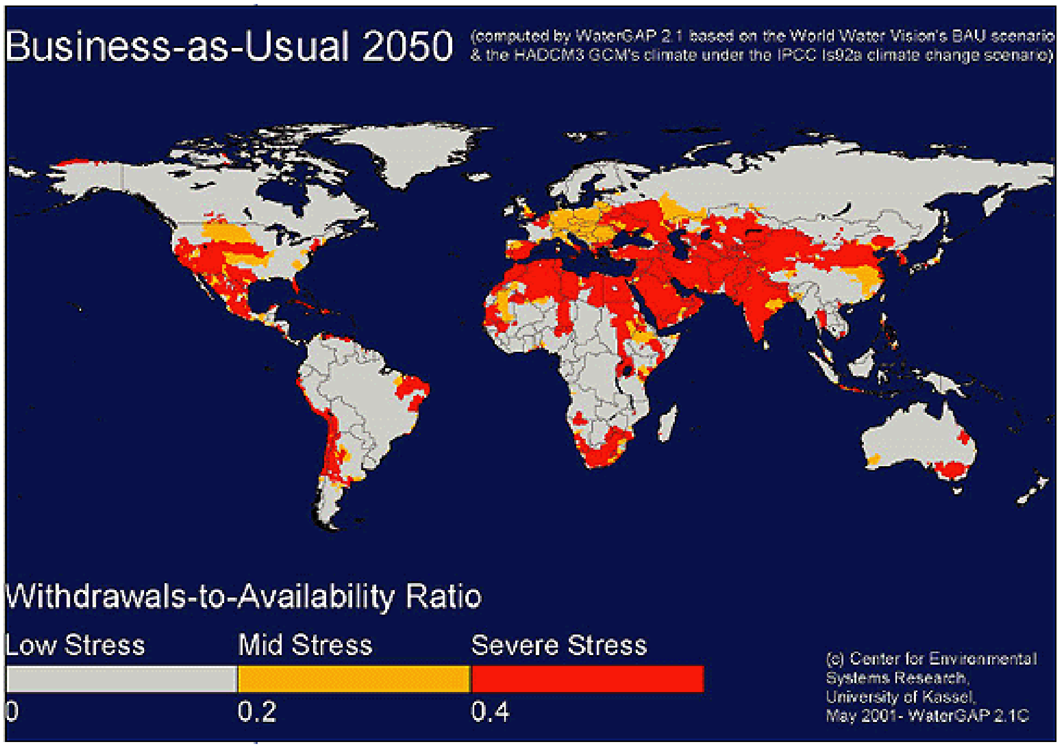
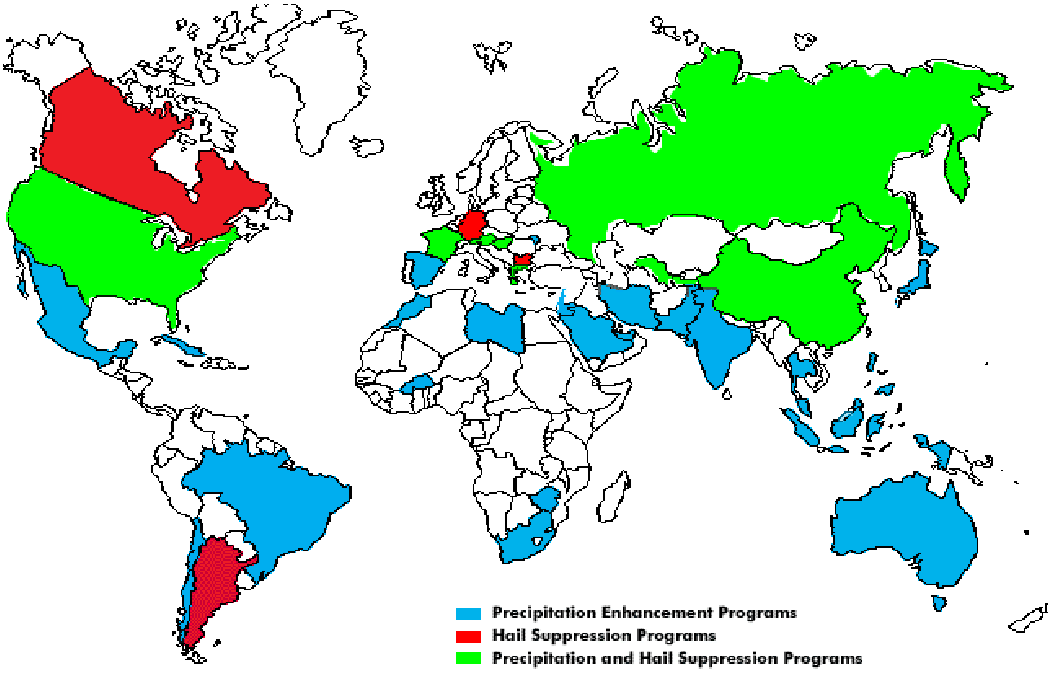


PLATE 1 It is projected that by 2025 some 3 billion people will live in countries that have less than 1,700 cubic meters per capita per year—the quantity below which humans suffer from "water stress" —and that number is expected to increase further by 2050. The figure shows global water stress distribution in 2050, under a business-as-usual scenario developed for the WaterGAP model of the Centre for Environmental Systems Research at the University of Kassel. SOURCE: Alcamo, Henrichs, Roesch: "World Water in 2025", Kassel (1999), [http://www.worldenergy.org/wec-geis/publications/reports/liow/stresses/water.asp].



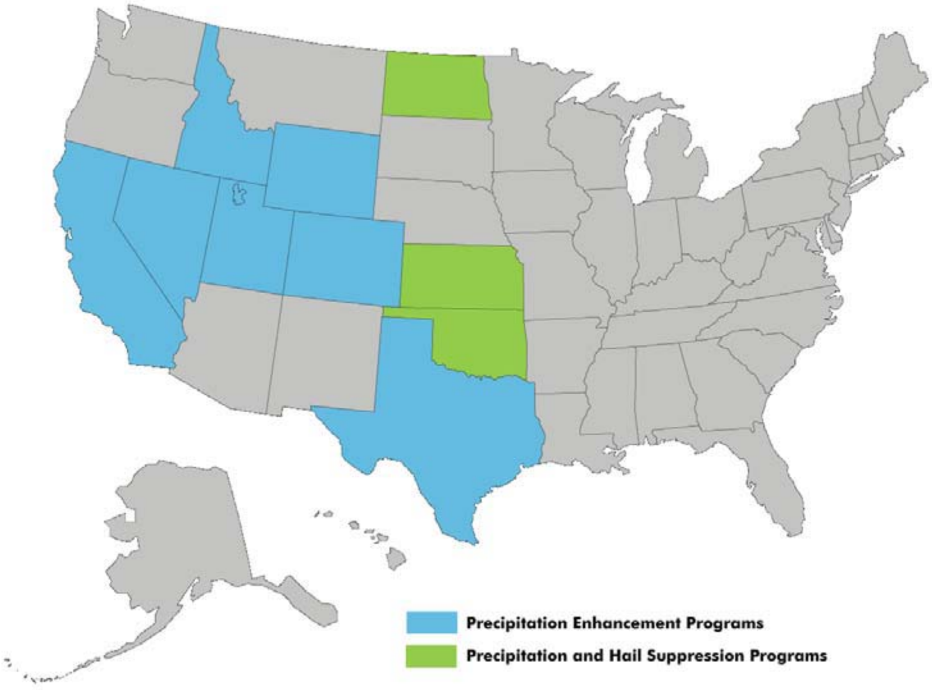


PLATE 2 Top: Countries that are conducting weather modification programs. Complied with information from WMO (1999) by R. Bruintjes. Bottom: States in the United States where weather modification programs currently are ongoing. SOURCE: Compiled from NOAA data by R. Bruintjes.

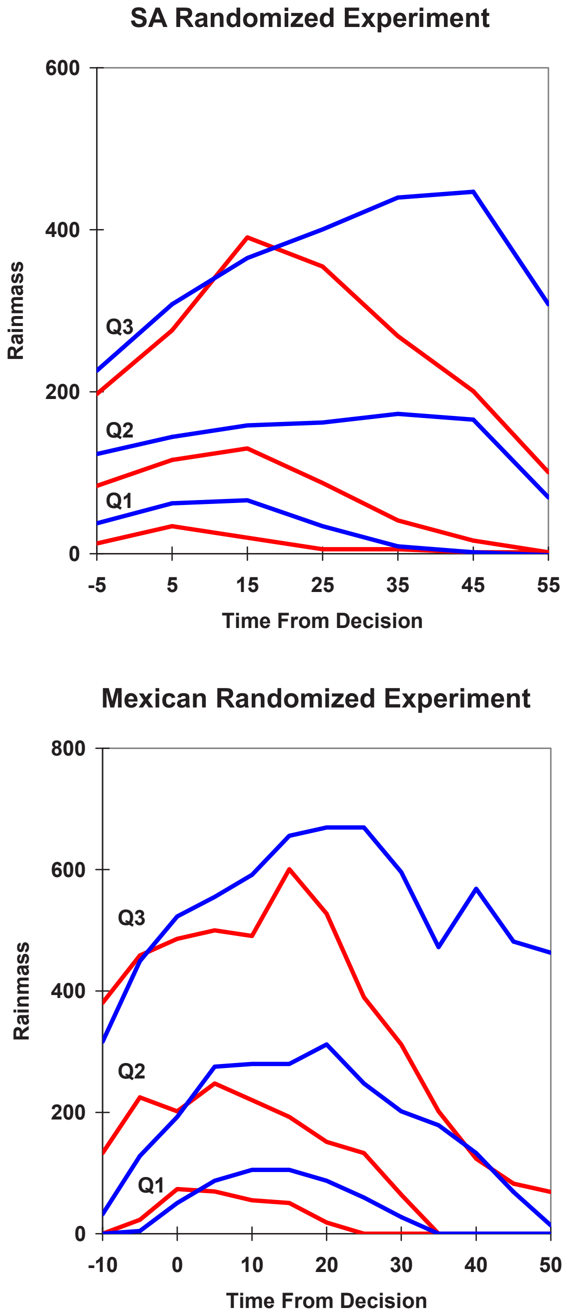


PLATE 3 Results from the South African (SA) and Mexican hygroscopic flare seeding experiments. The first (25 percent, Q1), second (50 percent or median, Q2), and third (75 percent, Q3) quartiles show radar-estimated rain mass (ktons) of the randomized seeded storms (blue line) and unseeded storms (red line) as a function of time from the randomized decision to seed or not. The time frame is divided into 10-minute intervals and is based upon the randomized seeding decision (0), ranging from 10 minutes prior (-10) to 50 minutes afterward (+50). SOURCE: Compiled by R. Bruintjes, National Center for Atmospheric Research.

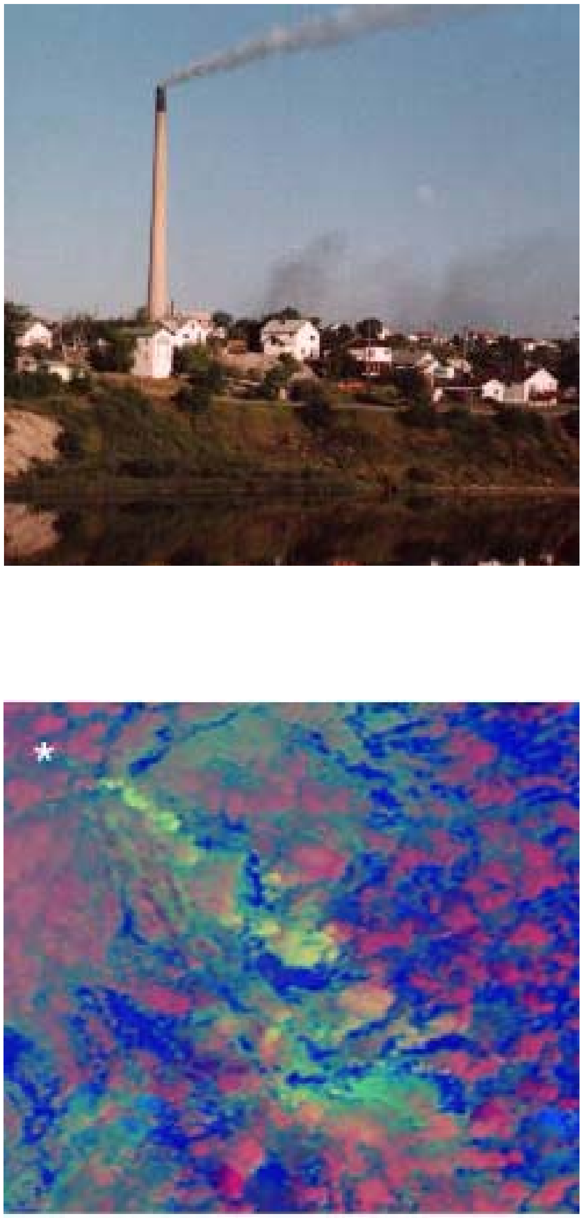


PLATE 4 This smoke stack of a mining complex in Manitoba, Canada, causes the pollution track originating at the white asterisk. Satellite remote sensing image of yellow pollution tracks in the clouds, due to reduced droplets size. SOURCE: Photo provided by W. L. Woodley, Woodley Weather Consultants. Image adapted from Rosenfeld (2000).

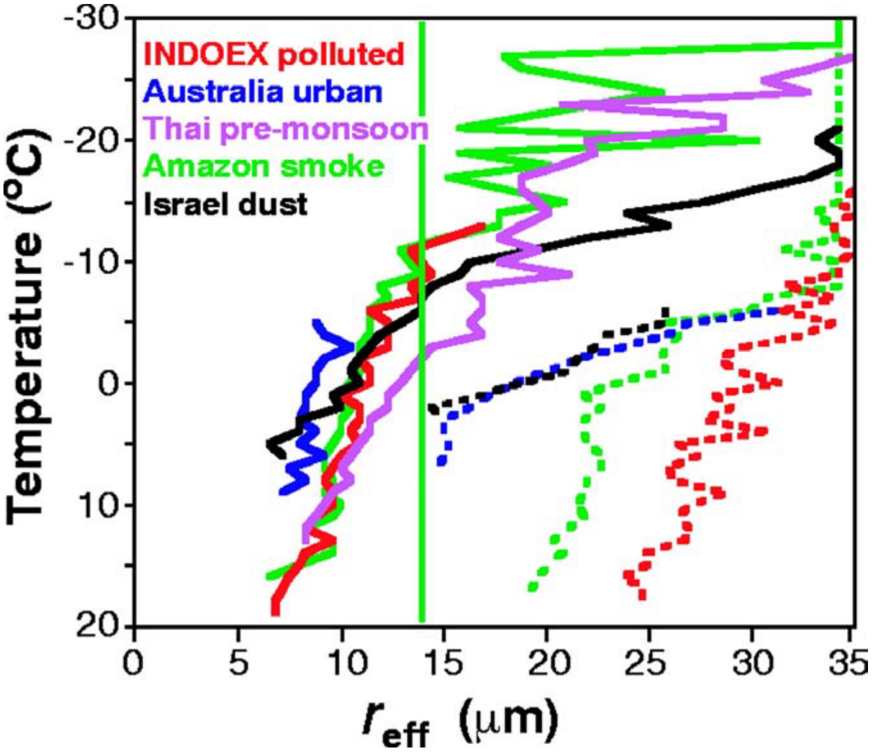


PLATE 5 Satellite-retrieved effective droplet (r_{eff}) radius near cloud top for polluted cases (solid lines) and corresponding pristine locations (broken lines). This suggests substantial alteration of cloud properties by anthropogenic influences in ways that might inhibit precipitation. SOURCE: Ramanathan et al. (2001).

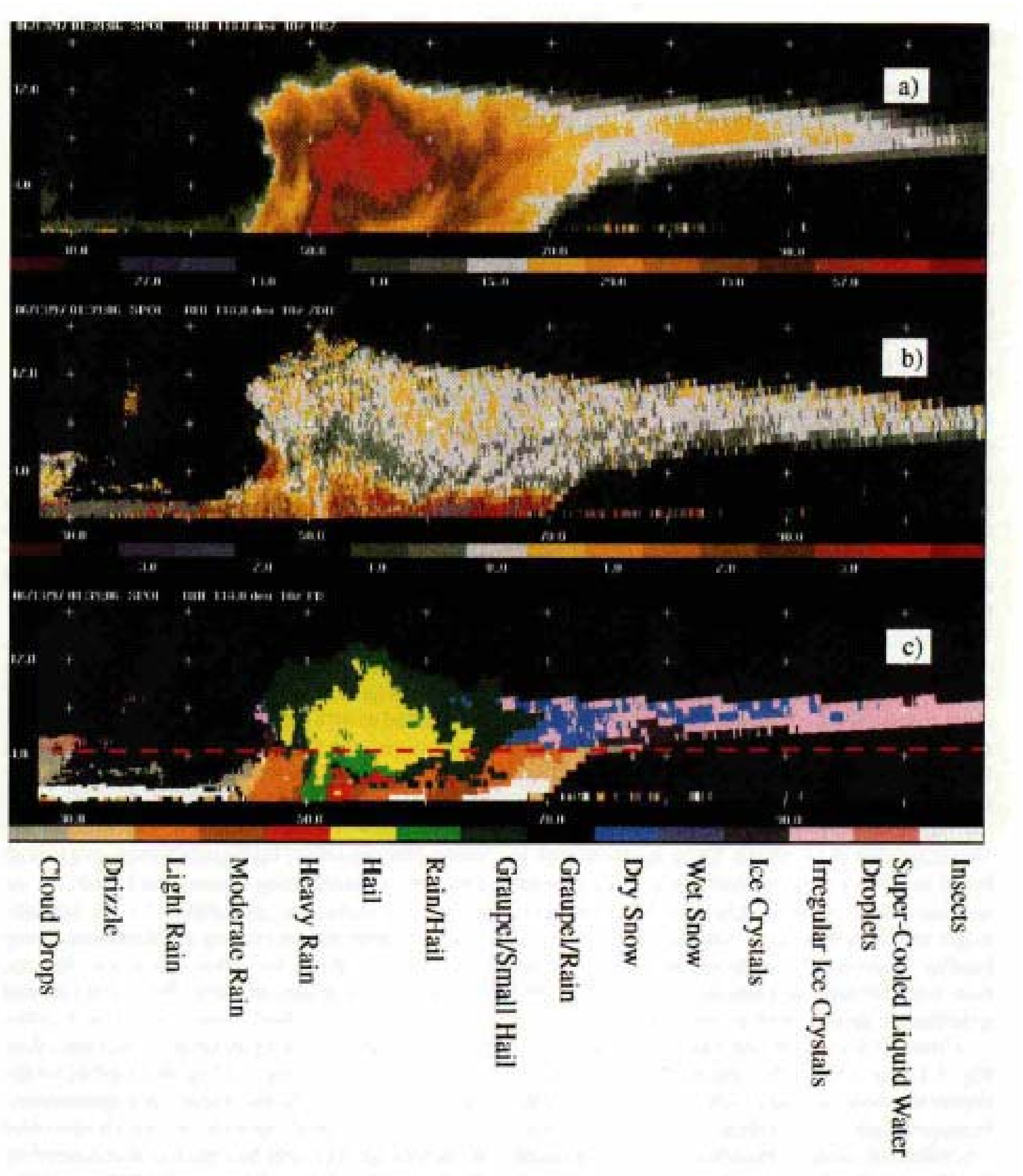


PLATE 6 Polarmetric radar observations of a mature thunderstorm. The data are from an RHI scan through a Kansas storm by NCAR's S-Pol research radar. (a) Reflectivity vs. ZDR for regions of liquid drops and hail. (b) Regions denoting 15 different hydrometer classes in color code. (c) Two-dimensional membership function in ZHH/KDP space. SOURCE: Vivekanandan et al. (1999).

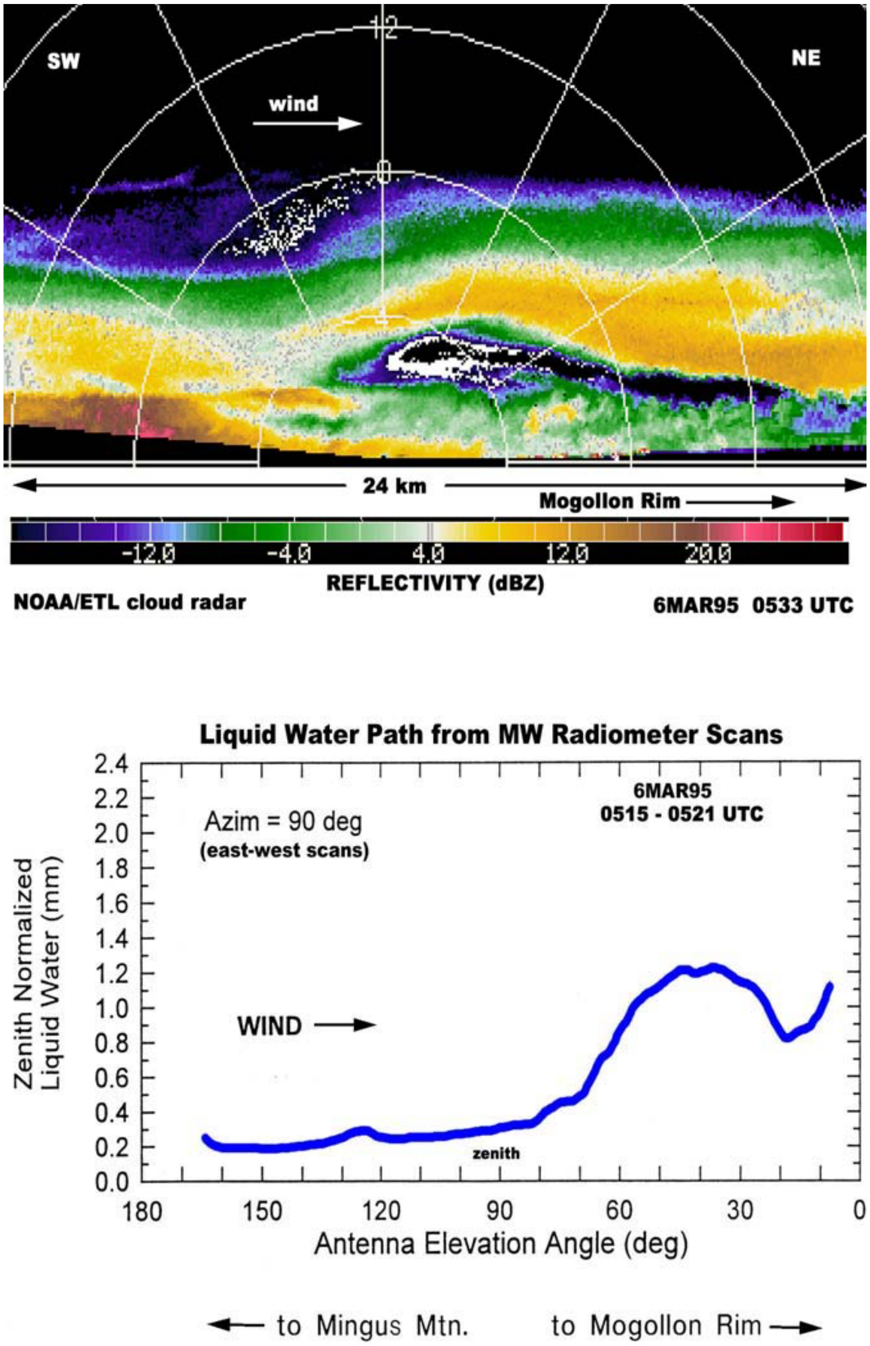
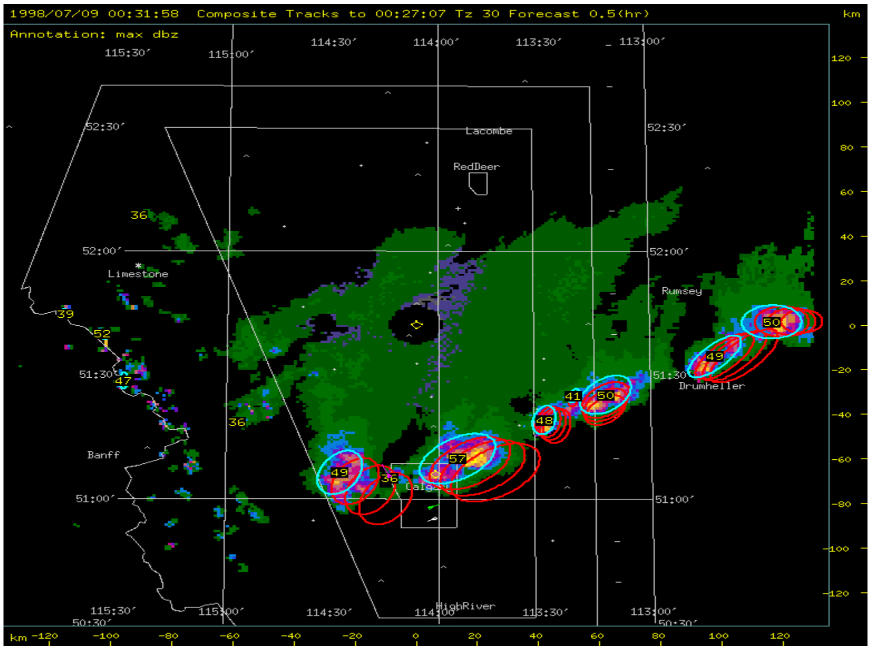
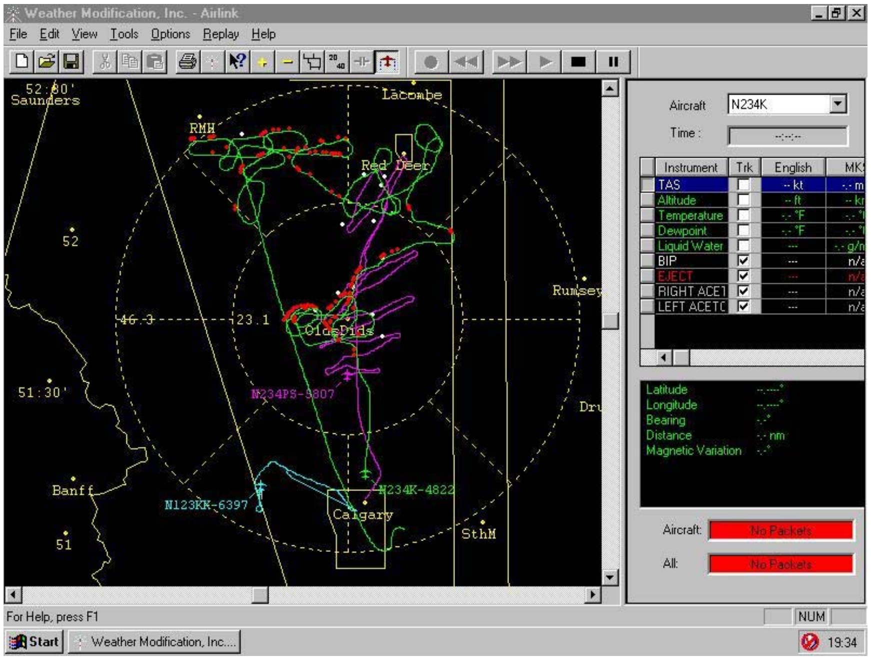


PLATE 7 An orographically induced standing wave of supercooled liquid across the Verde Valley (in Arizona) as observed by scanning cloud radar (top image), and by a microwave radiometer scan of liquid water path (bottom image) SOURCE: Reinking et al. (2000).





Aircraft N234K

Time : --:--:--

Instrument	Trk	English	MKS
TAS	☐	-- kt	-.- m
Altitude	☐	-- ft	-- k
Temperature	☐	-.- °F	-.- °
Dewpoint	☐	-.- °F	-.- °
Liquid Water	☐	---	-.- g/
BIP	☑	---	n/a
EJECT	☑	---	n/a
RIGHT ACET	☑	---	n/a
LEFT ACETC	☑	---	n/a

Latitude --.----°
Longitude --.----°
Bearing -.-°
Distance -.- nm
Magnetic Variation -.-°

Aircraft: No Packets

All: No Packets

PLATE 8 Top: Example of TITAN Storm Tracking. Bottom: Example of the use of GPS aircraft tracking. SOURCE: T. W. Krauss, Weather Modification Inc.