WEATHER MODIFICATION

Finding Common Ground

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The 2004 National Academies report on the future of weather modification research is examined by a panel representing the NRC and the Weather Modification Association.

The National Academies, at the request of the National Oceanic and Atmospheric Administration (NOAA), convened a workshop in November 2000 to review the current status of weather modification (Orville 2001). As a result of this workshop, NOAA asked the National Academies to carry out a study 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 (NRC 2003).

The report, entitled "Critical issues in weather modification research" was released by the National Research Council (NRC; NRC 2003) in October 2003 (see online at www.nap.edu).

In January 2004, the Weather Modification Association (WMA) provided a perspective from those involved in operational weather modification to the

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NRC report (Boe et al. 2004a) (see online at www.weathermodification.org). Other responses (e.g., from the North American Interstate Weather Modification Council), as well as coverage in the media, indicated widespread interest in this subject that suggested the implications of the NRC report as directed to NOAA might be discussed in a wider context.

Three members of the original NRC Committee (Michael Garstang, Roelof T. Bruintjes, Robert J. Serafin) met at the National Center for Atmospheric Research (NCAR) in May 2004, with four members of the WMA subpanel (Harold D. Orville, Bruce A. Boe, William R. Cotton, Joseph A. Warburton), in order to discuss their respective opinions regarding the two reports.

In the sections below, we summarize our views on areas where the NRC report and the WMA response agree, where they differ, and on some issues that were considered by the WMA but are not in the NRC report.

AREAS OF COMMON GROUND. The WMA response fully supports the principal conclusion of the NRC report that the field of atmospheric science is now in a position to answer many of the crucial questions that have impeded or blocked progress in weather modification in the past. Important advances in observational capacity, data acquisition, and processing, and in modeling scales of motion important to weather modification have been made over the past two to three decades. Only few of these advances have been employed in weather modification research or in operational programs. The NOAA Federal–State Atmospheric Modification Program (AMP) employed a number of these technologies. The North Dakota Thunderstorm Project (NDTP) in 1989 included the deployment of NCAR CP-3 and CP-4 C-band Doppler radars, the NOAA Environmental Technology Laboratory (ETL) X-band, circular-polarized Doppler radar, and a number of instrumented aircraft. A tracer-release aircraft was also employed (Boe et al. 1992). A similar but smaller-scale program the North Dakota Tracer Experiment (NDTE) was conducted in 1993 (Boe 1994).

Each of these programs demonstrates elements of current capabilities. The NRC report calls for a coordinated national program to conduct a sustained research effort in the areas of cloud and precipitation microphysics, cloud dynamics, cloud modeling, and cloud seeding. The program should embody a balanced approach of modeling, laboratory studies, and field measurements designed to reduce the key uncertainties that currently limit progress in weather modification. Uncertainties already recognized in the NRC report include issues in cloud/precipitation microphysics, cloud dynamics, and cloud modeling. The effort to reduce these uncertainties should capitalize upon existing field facilities and developing partnerships among research groups and operational programs. Such a research program should focus on understanding and "process" studies.

The NRC report reflects the view of the operational community drawing attention to two paradoxical situations.

- Large expenditures of state and other funds are currently being made supporting operational weather modification programs, but with little or no support from any source for research into weather modification. Consequently, critical uncertainties are not resolved, understanding of the chain of physical processes is not advanced, and the ability to demonstrate success or failure is impaired, perpetuating the perception that proof of concept is lacking, which then adversely affects support for research.
- The considerable scientific interest in understanding inadvertent weather modification, such as the modification of clouds, their radiative properties, and possibly precipitation due to anthropogenic aerosols, seems paradoxical compared with how little interest there is in understanding advertent weather modification, despite the fact that the physical principles underlying both are in many cases the same. Common ground exists in at least nucleation, microphysical, and radiative processes, and in consequences such as changes in temperature, column stability, cloudiness, and precipitation.

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. An effective research program should help to improve and optimize the operational programs. The water resources and land-use sectors should be an integral part of such a research effort. The development of a stable funding environment to develop a new generation of scientists working in this field is needed.

The NRC report advocates a stepwise research program that focuses upon and seeks answers to critical uncertainties impeding the understanding of the chain of physical processes that lead to rain, snow, or hail on the ground. It is essential that physical concepts, laboratory findings, and numerical models upon which weather modification must ultimately rest must be tested in the field. The NRC report advocates that such field studies need to progress stepwise from the simplified to the complex. The report does not recommend to NOAA that a large and sustained federally funded operational weather modification experiment be conducted before a series of identified questions are better understood. *It is important to note that the NRC committee was giving advice to NOAA regarding a federally funded operational program and was not making judgments about ongoing commercial or state-funded operational programs.* The NRC report supports field experiments that are founded upon clearly formulated hypotheses, including those that can be conducted in cooperation with operational programs.

In advocating a substantial increase in federal funding to weather modification research, the NRC report directs such support at critical areas of uncertainty. The report does not specify how the scientific community would use such support. Instead, the decision is left to researchers themselves to decide upon the specifics of the research, including the tools to be used (models, laboratory equipment, remote sensing, instruments, instrument platforms, etc.)

In terms of the principal conclusion of the NRC report, we believe that the NRC report and the WMA response differed in emphasis rather than substance. For example, the WMA believes that numerical models of cloud systems are more advanced than is implied by the NRC report, and that hybrid microphysical models such as used by Wobrock et al. (2003) might be used to accurately and realistically simulate natural hailfalls.

The need for the development of evaluation techniques applied in both seeding experiments and operational weather modification programs is recognized both in the NRC report and by the WMA response. The difficulty in applying randomization in operational programs and the need to develop testable physically based hypotheses places emphasis upon the ability to specify and observe critical physical processes.

POINTS OF DISAGREEMENT BETWEEN NRC REPORT AND THE WMA RESPONSE.

Differences in the perspectives on the research effort called for in the NRC report and the needs and demands of the operational weather modification community are identified in order of importance in the columns below. The discussion section that follows addresses the differing positions.

ISSUE 1: THE INTERPRETATION OF "SCIENTIFIC PROOF."

NRC Report. Scientific proof is interpreted as an understanding of processes that can be replicated by predictable, detectable, and verifiable results. With the exception of cold fog, and despite cases where there are strong indications of induced changes, the evidence available has not adequately met these criteria. This position does not challenge the scientific basis of weather modification concepts. Instead, it presents the challenge to find the right balance between assured knowledge and the need for action.

The level of noise in natural systems compared to the magnitude of the signal has made verification of either the enhancement of rain or snowfall or the reduction of hail extremely difficult. Lack of a clear understanding of the chain of physical processes in a cloud that eventually results in precipitation at the ground has compounded the problem of proof.

Considerable damage in the past was done to the cause of weather modification by unsubstantiated claims of success. Despite an increasing body of evidence that treatment can modify both the character of the clouds and the precipitation from these clouds, such results constitute evidence but not proof.

WMA response. The issue of scientific proof arose from the NRC panel statement that there was "no convincing scientific proof that cloud seeding worked" yet at the same time stated "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 WMA panel believes that global climate change and inadvertent weather modification would both fail the rigorous tests proposed for planned weather modification. In fact, the definition of scientific proof proposed by the NRC panel is sufficiently stringent that few atmospheric problems could satisfy it.

The problem is that scientists and nonscientists alike interpret the statements about no convincing proof that cloud seeding works, and ample evidence that inadvertent weather modification is a reality, as indicative that inadvertent weather modification has a much stronger foundation. But, there is also ample evidence that winter fog modification, snowpack augmentation, and glaciogenic and hygroscopic seeding to enhance rainfall are a reality, even though the magnitude of the effects may be difficult to precisely quantify (see the discussion and references in the WMA response; Boe et al. 2004a,b).

ISSUE 2: CURRENT STATUS OF CLOUD MODELS AS APPLIED TO WEATHER MODIFICATION.

NRC report. Numerical modeling is a key component of weather modification research. More powerful computing resources allow higher-resolution simulations that may have short-term predictive value. Such simulations can also involve a data assimilation process incorporating observational data from various and diverse types of sensing systems, which may improve the simulations or predictions. However, further improvements are needed in the representations of microphysical processes relevant to weather modification. The 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. It is urged 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) postoperational evaluation and analysis. These modes help to optimize cloud seeding procedures and to establish or refine physical hypotheses, and 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 also 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.

WMA response. A wide range of cloud and mesoscale models can and should be applied in weather modification research and operations, and is also proposed by the NRC report. These models apply various microphysics techniques (bin and bulk water methods) and various dynamical approaches (in one, two, and three dimensions). The use of hybrid microphysical models, which include hail spectra but otherwise use bulk water microphysics, should be especially helpful in simulating hail suppression concepts. Such a model has been used by Wobrock et al. (2003) to simulate natural hailfalls. This model indicates that there are fully three-dimensional storm models that predict the formation and evolution of hailstones in realistic hailstorm environments, contrary to a statement in the NRC report that no such models exist.

The use of bulk water microphysics continues to be developed for multidimensional cloud models and shows much promise (Milbrandt and Yau 2004, manuscript submitted to *J. Atmos. Sci.*). Early versions of such models have been used to predict cloud and precipitation development on field projects (Tuttle et al. 1989; Kopp and Orville 1994), with the results being presented before the day's operations were conducted.

These developments will be important for large-scale predictive models that cannot afford the luxury of bin-type microphysics.

To be useful the models do not have to predict every detail of the actual clouds that form (location, number of clouds, precise outline, etc.). The characteristics of the clouds, as to convective or stratiform, and their life histories (particularly their precipitation evolution) are the important items. Modification of the characteristics through cloud seeding lead to modification of their precipitation or hail production and can be predicted in multidimensional models today (Boe et al. 2004a,b and references above).

ISSUE 3: EVIDENCE FOR GLACIOGENIC SEEDING IN CONVECTIVE CLOUDS.

NRC report. Glaciogenic seeding has produced clear proof of microphysical changes to simple cloud systems with evidence based on statistical results that precipitation has been increased in some experiments.

WMA response. The evidence for precipitation enhancement of summertime glaciogenic cloud seeding is greater than concluded in the NRC report (see Dennis et al. 1975; Rosenfeld and Woodley 1989, 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.

1993, 1997; Woodley and Rosenfeld 2004). Summer cloud seeding experiments with glaciogenic seeding materials have developed innovative methods of evaluation using radar and satellite data that lead to greater understanding of the seeding effects.

Field work in Texas in the latter half of the 1980s led to refinement of the dynamic seeding conceptual model. Randomization of the seeding allowed comparisons to be made between the behavior of treated and unseeded convection systems using C-band weather radar. Results of the analyses indicated seeding with silver iodide more than doubled the amount of rain volume produced by the clouds (Rosenfeld and Woodley 1989). Moreover, the seeded systems lived an average 36% longer than their untreated counterparts, expanded to produce rainwater over an area 43% larger, and tended to merge with adjacent convective cells nearly twice as often. Both rainfall and merger statistics were significant at better than the 5% significance level. Intriguingly, the seeded clouds grew only marginally taller (about 7%) than the unseeded ones. These results confirm earlier results from the Dakotas (Dennis et al. 1975) that show broader and longer-lasting echoes, but only moderate height increases from the seeded cells in that region.

ISSUE 4: COLD SEASON OROGRAPHIC SEEDING.

NRC report. Orographic cloud seeding is identified as a particularly promising candidate for an intensive field experiment. 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 understanding of seeding effects and winter orographic precipitation.

A few important results from past projects 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 and in pronounced terrain;
- evidence of marked increases in ice particle concentrations leading to increased precipitation depending upon the availability of supercooled liquid water;

WMA response. This is another area that substantial agreement is found between the two reports with expansion of the concept made by the WMA. The WMA recommends that the winter project should be fully randomized and well equipped, and be conducted in the region of the mountainous west of the United States where enhanced precipitation will benefit substantial segments of the community, including enhancing water supplies in oversubscribed major water basins, urban areas, and Native American communities, for ranching and farming operations, and for recreation. This research should include "chain of events" investigations using airborne, remote sensing, and trace chemistry technologies from within and outside the target area. Model simulations should be used, once properly validated, as guidance toward determining optimum positioning and times of operation for ground-based and aircraft seeding. The work should include evaluations of precipitation, runoff, and recharge of groundwater aquifers. It should also include environmental impact studies, including water quality, hazard evaluations such as avalanches, streamflow standards, and protection of endangered species. Research is also recommended on seeding chemical formulations to improve efficiencies and on improving technology used in seeding aerosol delivery systems.

- reemphasis 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 iodide ice nuclei and other fast acting, highly efficient nucleating pyrotechnic and generator devices; and
- development of methods to detect traces of seeding agents in snowpack and rainwater.

The WMA response cited several projects and reports that indicated strong statistical and some physical evidence to support positive results of glaciogenic cloud seeding in wintertime operations and experiments. Of particular importance are the several articles supporting physical studies of field projects (e.g., Super and Heimbach 1992; Warburton 1994; Warburton et al. 1995a,b).

ISSUE 5: EVIDENCE FOR HAIL SUPPRESSION.

NRC report. Any theory of hail growth that is complete enough to serve as the basis for hail 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) variables such as ice nucleation, dominant rain formation, cloud-base temperature, environmental wind shear, and updraft strength and width, which are 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 multicell 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 has 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% in the study of Smith et al. 1997, and 27% 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 make these data difficult to interpret unambiguously.

Numerical models of storms have been and 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. Models powerful enough to include the details of the dynamics and microphysics in three

WMA response. The evidence that hail suppression is effective is quite compelling (Mesinger and Mesinger 1992; Rudolph et al. 1994; Smith et al. 1997; Dessens 1998). The WMA response report discusses hail suppression and hail suppression concepts in some detail.

Extensive research has been accomplished regarding hailstorms and hailstone growth since the 1970s. The National Hail Research Experiment (NHRE), conducted from 1972 through 1976, produced two volumes devoted to the topic (Knight and Squires 1982; also, see Warburton et al. 1982). Volume I concentrated on the general aspects of hailstorms of the central High Plains and volume II on several case studies of hailstorms observed during NHRE. Many field projects and scientific studies were conducted in western Canada during the Alberta Hail Project (Renick 1975) in the 1970s and 1980s. In Switzerland the Grossversuch hail experiment was run for five years during this period and produced many research papers (Federer et al. 1986; Lacaux et al. 1985). Numerous studies of convective storms continued through the 1980s and 1990s with several hailstorms among the sampled storms in the Cooperative Convective Precipitation Experiment (CCOPE), NDTP, and the NDTE programs. Studies of these storms and the growth of hailstones within the storms have led to the refining of several of the hail suppression concepts that guide most current operations. A recent review of hailstorms by Knight and Knight (2001) concentrates on the growth of hailstones. A worthwhile review panel response follows that review and elaborates on several of these hail suppression concepts. The Knights point out that there are nearly 1500 literature citations keyed to hailstorms and hailstones in the period from 1976 to 1996.

A full discussion of hail suppression concepts is included in the WMA response. We admit that a testable hypothesis is difficult to develop, but urge the community to develop one (or more). Concepts have been and are being used to guide operational 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.

hail suppression projects and should help focus future research experiments on hailstorms and hail suppression. Much of the material is used in the American Society of Civil Engineers' Standard Practice for the Design and Operation of Hail Suppression Projects. One of the primary lessons for future operational hail suppression projects learned from past projects is that the most effective seeding is done on the smaller, younger feeder cells.

ISSUE 6: SUPPORT FOR SPECIFIC PURPOSES.

NRC report. The NRC report advocates a substantial increase in federal funding to support a concerted and sustained research program in weather modification research. It recommends that existing national facilities should form the foundation for such a research effort, and that the opportunities offered by operational weather modification programs should be capitalized upon.

The NRC report advocates a stepwise research program that focuses upon and seeks answers to critical uncertainties impeding the understanding of the chain of physical processes that lead to rain, snow, or hail on the ground.

The NRC report explicitly does not attempt to identify the most important needs for facilities and tools to conduct such a research program. Instead, the decision is left to the researchers responsible for conducting such programs.

WMA response. The WMA recommends support for the following specific items or programs.

A storm penetration aircraft (instrumented and armored) capability should be maintained in the cloud physics and weather modification community. Certain critical measurements can only be made in situ by such an aircraft platform.

A cloud chamber facility should be developed and maintained that includes both isothermal and dynamic chambers for testing and developing new seeding materials and tracer technologies.

Much of the cloud seeding conducted today is done in situ by aircraft. A limited weather modification pilot training curriculum is presently in place at the University of North Dakota (comprising two semesters). This program should be expanded under the auspices of the national research program to improve the breadth of training provided, emphasizing flight in instrument meteorological conditions, and including actual hands-on, in-the-cockpit seeding experience.

DISCUSSION. Interpretation of the concept of proof in human intentional or inadvertent modification of weather emerges as the most important issue separating research and operational practitioners. The NRC report's definition of proof reflects accepted scientific criteria considered to constitute proof and is consistent with the American Meteorological Society (AMS) Policy Statement (AMS 1998). The WMA response sees proof in terms of sufficient evidence to justify action. This view is indeed acknowledged by the statement in the NRC report that scientific proof presents "the challenge to find the right balance between assured knowledge and the need for action." The issue of proof is thus complicated and can be modified by the specific demands exacted by prevailing conditions. "Ample evidence" can be used to justify action but can only be equated to "scientific proof" when that evidence meets the specified criteria for scientific proof. In practice, in a system as complex as the atmosphere, the burden of equating evidence to proof will remain and the issue will often be decided by forces outside of the scientific community.

The respective positions on issues 2, 3, 4, and 5 addressing the role of cloud models, evidence for glaciogenic seeding in convective clouds, cold season orographic cloud, and hail suppression reflect the difference in the perception of what constitutes substantiating evidence. In each case, the NRC position emphasizes advances and needs for research, while the WMA position points to operational findings and applications. Recognition of these two positions will help in charting the future course of weather modification research.

Both the NRC and the WMA urge renewed support of research into weather modification. The NRC leaves the details of how this support should be used to those conducting the work. The WMA suggests some high-priority facilities and programs that are needed to more effectively conduct future weather modification research and operations.

CONCLUSIONS. A common purpose in both the research and operational goals in weather modification is reflected in the NRC report and the WMA response. Substantial advances in understanding, observing technology, data acquisition and processing, and numerical modeling have occurred during the last three decades. During this same period, however, a progressive decline occurred in federal support for weather modification research. Despite this decline in support for weather modification research and over the same time period, operational weather modification programs in the United States and the rest of the world have grown in number. Evidence of intentional and unintentional effects induced by human intervention has simultaneously accumulated over the past 30 years. There is now considerable evidence, but not definitive scientific proof, that treatment can cause changes in clouds and cloud fields, and that the chain of physical processes leading to the formation of rain, hail, and snow can be changed. Despite these advances, critical links in the chain of physical processes that lead to precipitation remain unresolved. The inability to formulate or replicate critical parts of these complex chains of events limits the development of testable hypotheses and the design of confirmatory experiments. Many of the obstacles to progress are, however, now better identified.

The relevant processes are potentially observable and simulated numerically. The ability to focus upon these uncertainties and to remove or reduce these obstructions to progress is now very real. Many of these processes, such as the role of aerosols in cloud and precipitation formation, are common to both intentional and unintentional weather modification. Conducting controlled weather modification experiments and capitalizing upon operational programs will advance understanding in both deliberate and inadvertent weather modification.

Increasing demands for water and the increasing cost to society inflicted by severe weather require that the scientific, operational, and administrative communities combine in a sustained effort to determine whether and to what degree humans can influence the weather. The collective intellectual and technical resources now at our disposal, if applied with determination, will provide answers to these pressing questions.

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