A Response By The

Weather Modification Association

to the

National Research Council's Report Titled

"CRITICAL ISSUES IN WEATHER MODIFICATION RESEARCH"

The Report of a Review Panel

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CONTENTS

1. Executive Summary

The Weather Modification Association (WMA) is an association of scientists, engineers, economists, water management professionals, government and private business people, and others who have spent and continue to spend their careers working in the field of weather modification. The members, having read the National Research Council's report "Critical Issues in Weather Modification Research", issued last October 13, have helped prepare this response to that report. The NRC panel was asked to identify critical uncertainties limiting advances in weather modification science and *operations* and to identify future directions in weather modification research and operations for improving the management of water resources and the reduction in severe weather hazards, among other things. They were to do this even though the panel members collectively had very limited experience or knowledge in weather modification operations, especially in recent years.

This current panel was organized to prepare a WMA response to the NRC report concerning issues having operational impact or scientific consequences on operational projects and to provide additional information to the members of the WMA and the public. The national press seized on the conclusion of the NRC panel that there was no convincing scientific proof that cloud seeding worked, not realizing that the panel had opted for a definition of scientific proof that few atmospheric problems could satisfy. On the other hand, the NRC panel concluded, "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". We think, however, that global climate change and inadvertent weather modification would both fail the level of proof applied to planned weather modification. We nevertheless strongly support the NRC's recommendation to establish critical randomized, statistical experiments along with the necessary physical measurements and modeling support to reduce the many uncertainties that exist in the science of weather modification.

In addition, the NRC panel cited a much earlier NRC report (NRC, 1964) which suggested that the initiation of large-scale operational weather modification would be premature. We think that it is inappropriate for a national academy panel, with very limited operational weather modification experience, to make such a judgment. Citation of the very dated 1964 report suggests that little has changed since that time. The NRC panel notes operational programs in 24 countries and at least 66 large-scale operational weather modification programs in the U.S. The WMA believes large-scale operational programs have produced and continue to produce positive effects for society. The WMA does not agree with the NRC suggestion that implementation of large-scale operational programs would be premature. This response details the myriad changes and advances that have been made, but that were largely neglected by the current NRC report.

This WMA panel has added information on hail suppression, winter orographic cloud seeding, summer operational programs, and numerical modeling of cloud seeding effects to fill in for obvious gaps and weaknesses in the NRC report. A few other topics are also commented upon.

We support many of the recommendations of the NRC panel, but add several of our own:

- We support the NRC recommendation that there be a renewed commitment to advancing our knowledge of fundamental processes that are central to the issues of intentional and inadvertent weather modification.

- We support the NRC recommendation that a coordinated national program be developed to conduct a sustained research effort in the areas of cloud and precipitation physics, cloud dynamics, cloud modeling, laboratory studies, and field measurements designed to reduce the key uncertainties that impede progress and understanding of intentional and inadvertent weather modification. *But, we argue that the coordinated national program should also support exploratory and confirmatory field studies in weather modification. It should capitalize on operational cloud seeding programs, and use them as a basis for testing models, and developing new statistical methods for evaluating the efficacy of those operations.*

- We support the NRC conclusion that a coordinated research program should capitalize on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems.

- The Board on Atmospheric Sciences and Climate workshop report (BASC, 2001) recommended that a "Watershed Experiment" be conducted in the mountainous West using all of the available technology and equipment that can be brought to bear on a particular region which is water short and politically visible from a water resource management perspective. We strongly support this earlier recommendation that was not then included in the NRC report. Such a "Watershed Experiment" should be fully randomized and well equipped, and be conducted in the region of the mountainous West of the U.S. where enhanced precipitation will benefit substantial segments of the community, including enhancing water supplies in over-subscribed 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 and remote sensing technologies, along with trace chemistry analysis of snowfall from the target area. Model simulations should be used to determine optimum positioning and times of operation for ground-based and aircraft seeding. The work should include evaluations of precipitation, run-off, and recharge of ground water aquifers. Also, it should include environmental impact studies including water quality, hazard evaluations such as avalanches, stream flow 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.

- We recommend the application of existing and newly developed numerical models that explicitly predict transport and dispersion of cloud seeding agents and activation of cloud condensation nuclei, giant cloud condensation nuclei, and ice nuclei, as well as condensation/evaporation and collection processes in detail, to the simulation of modification of clouds. We concur with the need to improve and refine models of cloud processes, but existing models can be used as a first step to examine, for example, the possible physical responses to hygroscopic seeding that occur several hours following the cessation of seeding. In addition, existing models can be used to replicate the transport and dispersion of ground-based and aircraft-released seeding agents and the cloud and precipitation responses to those seeding materials in winter orographic clouds. Existing models can also simulate static and dynamic seeding concepts for fields of supercooled convective clouds. Moreover, existing models can be used to improve the efficiency of the operation of weather modification research projects and operational programs, and be deployed in the assessment of those programs.

- We recommend that a wide range of cloud and mesoscale models be applied in weather modification research and operations. This includes various microphysics techniques (both bin and bulk-microphysical models have their uses) and various approaches in the dynamics (all dimensionalities - one, two, and three dimensional models - offer applications). The application of hybrid microphysical models should be especially useful in simulating hailstorms and examining various hypotheses and strategies for hail suppression.

- We recommend that a concerted effort be made in the field and through numerical modeling, which includes simulations of hailstone spectra, to study hailstorms and the evolution of damaging hailstones as well as examine potential impacts of modified hailstone spectra on the severity of storms. Because operational programs regarding hailstorms are currently being conducted in the U. S., we encourage the "piggybacking" of research on such projects. We also encourage active cooperation with international hailstorm projects to elicit data and information concerning suppression concepts and technology.

- We recommend that an instrumented armored-aircraft capability (storm penetration aircraft, or SPA) be maintained in the cloud physics and weather modification community. This is essential for the in situ measurements of severe storm characteristics and for providing a platform for some of the new instruments described in the NRC report.

- We recommend that support be given for the development of innovative ways to evaluate operational cloud seeding projects. This is particularly important for the establishment of the physical basis of various cloud seeding methods and for establishing the possible range of cloud seeding effects.

- We recommend that evaluation techniques presently being applied to operational programs be independently reviewed, and as necessary revised to reduce biases and increase statistical robustness to the extent possible. Recognizing that randomization is not considered to be a viable option for most operational seeding programs, we acknowledge that there is much room for improvement in most present evaluations, many of which are presently done in-house.

- We recognize that much of the cloud seeding conducted today, and likely in the future, is done in situ by aircraft. A limited weather modification pilot training curriculum presently is in place at the University of North Dakota (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 IMC (instrument meteorological conditions) and including actual hands-on, in-the-cockpit seeding experience. Correct targeting is mission-critical, yet nationally, many pilots presently working on operational programs receive only limited training, many not having the benefit of any formal training whatsoever. When pilots are undertrained, project results are likely to suffer. A certification program for pilots by an organization such as the WMA, which, in addition to formal university instruction might include periodic recertification and/or recurrency training, would significantly improve the overall abilities and capabilities of the operational weather modification pilots.

We encourage the scientific and operational communities in weather modification to cooperate and work together whenever and wherever possible to solve the many problems slowing progress in the field. The future should not involve solely operational programs or research efforts. The two should be coupled whenever possible, to work together toward the many common goals.

2. Introduction

The National Research Council (NRC) released a report on 13 October 2003, titled "Critical Issues in Weather Modification Research" (NRC, 2003). The national press highlighted one of the committee's conclusions 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 the evidence has not been subjected to tests of significance and reproducibility". The NRC report makes a case for the decline of coordinated, sustained funding of research in weather modification during the last three decades. This decline in funding is cited as both an effect of and a cause of a lack of scientific proof of the effectiveness of cloud seeding. The panel was careful to say that, "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".

The Weather Modification Association (WMA) is an association of scientists, engineers, economists, water management professionals, government and private business people, and others who have spent and continue to spend their careers working in the field of weather modification. The WMA's executive committee believes that it is the association's responsibility to review the NRC report and to offer scientific and operational perspectives, supplemental information, rebuttal, and further recommendations. Taking this action is consistent with the WMA's vision, mission, and charter; see http://www.weathermodification.org/organization.htm. The executive committee charged the president, Richard Stone, to appoint a panel of WMA members to provide an assessment and response to the NRC report, to update the members and provide additional information to the public. A balanced panel was formed in early November composed of six members with expertise in hail suppression, winter orographic cloud seeding, precipitation enhancement, and numerical modeling.

The panel met in Fort Collins on December 5 and 6 to begin to prepare this report. All members except George Bomar were able to attend the meeting. He participated via e-mail and phone calls. In addition the members of the WMA were asked to provide information and ideas to the panel and to review an early version of the draft response. Many WMA members provided input. The panel takes full responsibility for the contents of this response. The members of the WMA panel and their backgrounds are given in the Appendix.

The statement in the NRC report of "no convincing scientific proof…." depends on their definition of scientific proof that involves randomized experiments, strong statistical support, extensive physical measurements and understanding, and replication. This is a very high standard for a system as complex as the atmosphere. They conclude, "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". They are thus clearly maintaining "higher bar" criteria for acceptance for planned weather modification. In our opinion, all should be evaluated with the same criteria. If inadvertent modification of weather and climate were held to the same standards of assessment as planned weather modification, they would have to conclude “that the limitations and uncertainties of the models and the lack of physical evidence, and the inability to assess cause and effect statistically, leads one to conclude that there is no convincing proof that human activity is affecting weather and climate”. *Indeed, if the NRC panel were to hold inadvertent weather modification and climate change theories to the same high standard, they could only conclude that there is "no convincing scientific proof" for either.* This having been noted, there is convincing scientific evidence of positive effects in several areas of weather modification, which will be cited below.

The NRC report, in its conclusions, quoted a statement from an NRC 1964 report, stating that the initiation of large-scale operational weather modification programs would be premature. We believe that this is a political statement made by a scientific panel with little recent experience or background in operational weather modification programs. Even the scientist who has asked for better scientific proof has encouraged the continued pursuit of cloud seeding programs where they are scientifically and operationally appropriate (Silverman, 2003, p 1227). In any event, this panel believes it to be inappropriate for a national scientific panel to make such judgments on a technological industry that has been in existence for nearly fifty years and has provided much scientific evidence, much of it in the refereed scientific literature, concerning weather modification and cloud physics.

The recent NRC report leaves much to be desired in a review of research and operations in weather modification. This is not unexpected, inasmuch as the NRC committee had no members from the operations community and lacked depth in weather modification research. The absence of expertise in hail suppression and orographic cloud seeding was especially notable, as was the lack of experience in the modeling of cloud seeding effects. These deficiencies resulted in a report that emphasized the NRC committee’s expertise, i.e., experience in weather modification through the 1970’s, convective cloud seeding via hygroscopic seeding methods, and the advances in instrumentation that bode well for future research projects.

In the following review we discuss the basis for hail suppression, the capabilities in cold season cloud seeding projects, some additional information on summertime cloud seeding projects, the ability of cloud and mesoscale models to simulate weather modification experiments and operations, and other perceived omissions or mis-statements in the NRC review. We close our main response with our conclusions and recommendations.

3. Supplemental Information to the NRC Report

3.1 Hail suppression

Extensive research has been accomplished regarding hailstorms and hailstone growth since the 1970's. The National Hail Research Experiment (NHRE), conducted from 1972 through 1976, produced two volumes devoted to the topic (Knight and Squires, Eds., 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 70's and 80's. In Switzerland the Grossversuch hail experiment was run for five years during this period and produced many research papers (Federer et al., 1986). Numerous studies of convective storms continued through the 80's and 90's with several hailstorms among the sampled storms in the Cooperative Convective Precipitation Experiment (CCOPE), the North Dakota Thunderstorm Project (NDTP), and the North Dakota Tracer Experiment (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.

3.1.1 Hail suppression concepts

The NRC review panel failed to discuss the rationale and any conceptual model for hail suppression. We provide such a discussion here, basing it largely on a World Meteorological Organization (WMO) report (WMO, 1996), and the Board on Atmospheric Sciences and Climate (BASC, 2001) report, which in turn depended on the many research studies and field experiments reported in the literature in the past 30 years.

Three ingredients are necessary to produce hail: (1) the raw material from which the stones develop (supercooled liquid water, or SLW), (2) nascent hail embryos (commonly graupel and/or frozen raindrops), and (3) updrafts of sufficient magnitude to support the growing hailstones. If any of the three are absent, hail does not develop. When all three are present, the hail growth is limited by the available SLW, and/or the updraft strength. It logically follows that ample SLW and updraft, coupled with limited numbers of hail embryos, will result in the largest hailstones the updrafts can support. When the hailstones grow to the maximum mass supportable by the updraft, they begin to descend. If the stones are not too large and the subcloud layer warm, significant melting occurs during descent, and those hailstones reaching the ground are likely to be small.

Thus, the most often cited hail suppression concept is intended to increase the numbers of nascent hail embryos, and thus, through competition, reduce the amount of supercooled liquid available to grow hail. Instead of growing hailstones large enough to survive the transit through the warm subcloud layer, the available SLW is depleted by the formation of greater numbers of smaller ice particles (smaller hailstones) that are more likely to melt during descent. This concept is known as *beneficial competition*.

Beneficial competition is produced by the introduction of additional hail embryos to the flanking cells of a hailstorm. In theory this would lead to more numerous and smaller hailstones, which would melt more, or perhaps entirely during their descent. A risk is that too few embryos could be added to some inefficient storms and more hailstones could be produced.

Another concept, *early rainout*, is based upon the initiation of the ice-phase precipitation process earlier in the lifetimes of supercooled convective clouds. For example, if ice-phase hydrometeors can be made to form when cloud top temperatures are $-5^{o}C$ rather than $-15^{o}C$, precipitation can form earlier in the clouds' lifetimes. When this is made to happen within the flanking line, several positive effects may result.

First, precipitation falls from what would have otherwise have been rain-free cloud base, possibly in areas of low-level storm inflow. This could impede or retard the moisture flux into the storm, which in turn could lessen the condensate (and eventually SLW) in the stronger updrafts.

Second, conversion of SLW to ice in the smaller turrets reduces the net SLW available for hail growth in the larger turrets, where updrafts are stronger and more conducive to the growth of larger hailstones.

Third, the earlier release of latent heat fuels the buoyancy of the smaller, less vigorous turrets.

Fourth, the total area receiving precipitation from the storm may be increased, while the intensity and amount of precipitation produced within the main storm core may be slightly lessened.

Early rainout is theoretically achieved by the same seeding strategy as that used for beneficial competition. In successful early rainout modification, the precipitation falls from the cells before ingestion into the mature main cell. If the ice hydrometeors produced by seeding do not grow large enough to precipitate from the rain-free cloud base, the number of nascent hail embryos has been increased, aiding beneficial competition.

The term *trajectory lowering* is born of the notion that maximum hailstone growth occurs at higher, colder altitudes, where supercooling is very significant. Such being the case, trajectory lowering would logically slow and/or lessen hail development. One could say that early rainout is in fact also trajectory lowering. More complete knowledge of the optimum hail growth regions begs for the deployment of polarimetric radars.

Trajectory lowering might also be derived from updraft loading resulting from rapid hydrometeor development within treated flanking line turrets. The additional total water mass could slow the updraft, diminishing the storm's capacity for producing hail.

Promotion of coalescence of cloud droplets is accomplished by seeding the flanking cells with hygroscopic materials near cloud base. Such treatment may cause early rainout and/or trajectory lowering. It may also lead to the production of additional hail embryos because of the freezing of large raindrops, which could in turn enhance beneficial competition. Hygroscopic seeding promotes coalescence and is thus thought to affect hail production.

The earlier release of latent heat (see early rainout, above) would help release convective instability within the smaller turrets, collectively over a larger area than in the central mature cell. This could change storm dynamics, and as with the other concepts previously stated, would be well suited to numerical modeling and simulations.

In addition, whenever precipitation falls out of clouds, downdrafts and outflows are formed in the subcloud layer, further changing storm dynamics.

Another concept used in the past was *complete glaciation*. The aim of hail suppression by glaciation is to introduce so many ice crystals via seeding that the ice crystals consume all the available supercooled liquid water as they grow by vapor deposition and riming of cloud droplets. To be effective this technique requires the insertion of very large amounts of seeding materials in the storm updrafts. Modeling studies (Weickmann, 1964; Dennis and Musil, 1973; English, 1973; Young, 1977) have suggested that unless very large amounts of seeding material are used, the strongest updrafts remain all liquid and hail growth is not substantially affected. Therefore, the glaciation concept is generally thought not to be a feasible approach to hail suppression. The glaciation concept is also not popular because many scientists think that it may result in a reduction in rainfall along with hail. Since most hail-prone areas are semi-arid, the loss of rainfall can have a greater adverse impact on agriculture than economic gains from hail suppression.

Figure 1 depicts these concepts of seeding in a multicell thunderstorm. Developing flanking line cells with weaker updrafts are shown on the left of the figure and the mature cell with strong updrafts on the right. In multicellular storms, the developing cells of the flanking line each in turn mature, becoming the dominant cell, which eventually weakens and rains out. To better understand the figure, it is helpful to consider the horizontal axis to represent time with zero on the left and the time of the dissipating cells on the far right.

Important things to note from this discussion are that the concepts dictate that developing cloud turrets are treated, invariably cumulus congestus, rather than the main cell cumulonimbus. This means treatment of young clouds with modest updrafts, not the mature cells with strong updrafts. Also, note that precipitation development is accelerated. Promotion of coalescence is directed at liquid-phase processes primarily; the other methods are based largely on glaciogenic seeding effects. Dynamic effects result from the release of latent heat (primarily from freezing), and from redistribution of condensed water within the targeted cloud turrets.

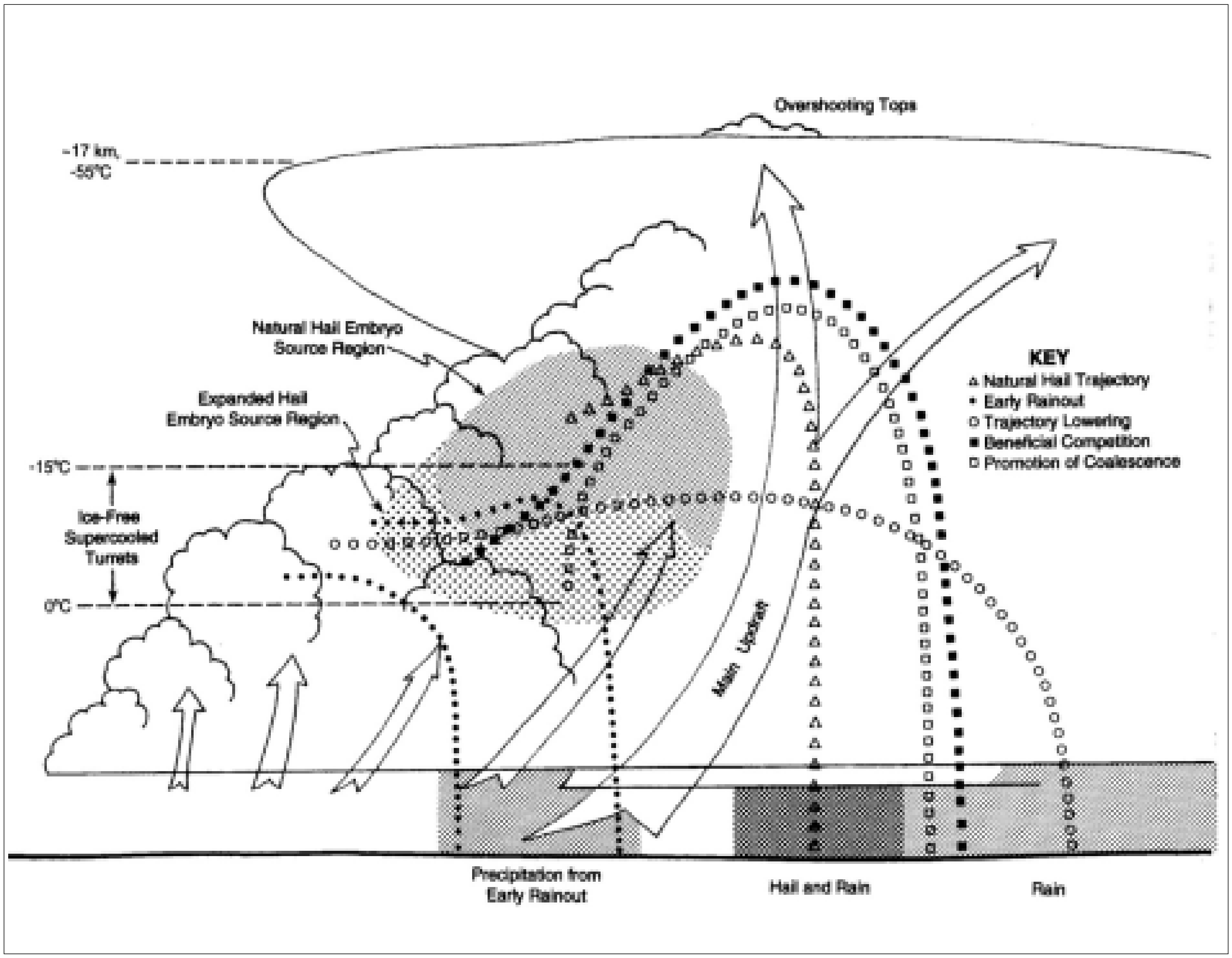

Figure 1. Hail suppression concepts, from WMO Technical Document No. 764, 1996.

3.1.2 Evidence of cloud seeding effects

Progress in the numerical simulation of hailstorms and hailstone evolution has occurred, and is discussed below in Section 3.4. Contrary to statements in the NRC report, there are reasonable models that simulate the development of hail in realistic hailstorm environments. Cloud seeding simulations show the effects of early rainout and beneficial competition in reducing hail from relatively efficient hailstorms, but the possible increase of hail and rain from some relatively inefficient storms. The models also show the location of hail embryos close to the forward region of the major updraft. The major growth of the ice particles occurs in high liquid water regions between -5°C and -35°C, usually between -10°C and -25°C. Trajectory analyses indicate that particles that grow to relatively large size begin their major growth cycle in a very narrow ribbon-like region in an area of weak updraft near the updraft/downdraft interface on the forward flank of the storm cells (Farley et al., 2004a, Farley and Orville, 1999), in agreement with recent observations (Thompson and List, 1999).

The NRC report quoted results from Smith et al. (1997) showing a 45% decrease in crop damage due to hail suppression in a nonrandomized operational project, but cast doubt on the results with some unpublished analysis using ratios. Further examination of Fig.2.1 in the NRC report suggests that the analyst picked a starting point that would bolster his point. In addition, the use of ratios in precipitation records requires extreme care. Normally a scientist being corrected or challenged on a conclusion is afforded the opportunity to respond. That such an opportunity was not offered here suggests a possible negative bias on the part of the NRC committee, although we realize that NRC panels do not normally invite comments and responses.

Other evidence exists indicating decreased hail damage during hail suppression efforts. Mesinger and Mesinger (1992) examined 40 years of operational hail suppression data in eastern Yugoslavia. After attempting to remove the effects of climatic fluctuations during the period, they estimated that the hail suppression projects reduced the frequency of hail between 15 and 20%. Rudolph et al. (1994) reported on results from a randomized crossover hail suppression experiment conducted in northern Greece during 1984-1988. Data were collected on 37 days from a total of 196 hailpads spaced an average 4.5 km apart. Hailstone size distributions showed clear evidence of beneficial treatment effects. Aircraft seeding using silver iodide (AgI) generators and flares, primarily on flanking feeder cells, was employed. Target hailpad counts (impacts) ranged from 38% to 100% less than control counts in all 12 size categories, with an average reduction of 55%. On an annual basis, P-values ranged from 0.002 to 0.02. Dessens (1998) in a long running operational program using AgI ground generators and hailpads in southern France found a 42% decrease in hailstone number using target-control analyses.

As in most research on operational programs in cloud seeding there are problems of targeting the seeding agent. Chemical tracers are a key to determining the extent to which a target area is covered. Linkletter and Warburton (1977) found that during the NHRE the AgI was broadly dispersed when weak, poorly organized storms were seeded, but that the seeding agent was confined to only limited regions of the more vigorous storms that had well-defined internal circulation patterns. In the 18 storms seeded in 1973 and 1974 only 50% of the 1973 storms and 70% of the 1974 storms had "seeding" silver above background concentrations. Based upon theoretical predictions, less than 10% of the storms had enough silver to represent a significant seeding effect. Further analysis of four storms in NHRE (Warburton et al., 1982) revealed that the seeding results appeared to fall into three categories; those where the AgI concentration was relatively constant over a wide range of precipitation amounts; those where the precipitation amounts were small and independent of silver contents; and those where there is a positive correlation between silver concentration and precipitation amount. In the cases with positive correlation, the seeding was associated with a precipitation increase of about 1.7 mm depth of water per square meter.

Similar coverage results were found by chemical analyses in Grossversuch IV (Lacaux et al., 1985). Two cells on one day showed 7% and 25% coverage and two cells on two other days had seeding coverage of 100% and residence times, in cloud colder than -5ºC, of 500 to 700 seconds.

Another concern about hail suppression is its impact on rainfall. Because hailstorms often occur in semi-arid regions where rainfall is limited, Changnon (1977) estimated that in general, the destructive effects of hail damage are often outweighed by the positive benefits of rainfall from those storms. This is, of course, not true for certain high-risk crops such as tobacco, grapes, or certain vegetables. Modeling studies like Nelson (1979) and Farley and Orville (1982) suggested that rainfall and hailfall are positively correlated so that reductions of hailfall coincide with reductions in rainfall. Later modeling studies with better microphysics, carried out by Farley (1987) and Farley et al. (2004b), showed less hail and more rain in the seeded cases. In addition, an evaluation of rainfall from an operational hail suppression program in Alberta, Canada by Krauss and Santos (2004) suggested that seeding to reduce hail damage also resulted in an increase in rain volume by a factor of 2.2. Consequently, the effects of hail suppression on rainfall needs further study and measurement on research and operational projects.

At present the design of a randomized hail suppression experiment involving response variables measured at the ground (with the objective of substantiating a hail suppression effect) appears to be impractical, but should be a research goal. The required size of the instrumented target area and/or duration of such an experiment are prohibitively expensive. Moreover, funding agencies are very cautious about committing their resources to supporting a program of more than 5 years duration. Randomized experiments such as Grossversuch IV were designed with the intent to discern a seeding signal in a 5-year period based on the optimistic expectation of a 60% reduction in kinetic energy of falling hail (Federer et al., 1986). Note that Mesinger and Mesinger's (1992) evaluation of the 40-year long hail suppression program in Yugoslavia suggested only a 15-20% reduction in hail frequency. Thus a funding agency would have to be committed to supporting a randomized hail suppression experiment for 10 years or more! Scientific understanding sufficient to sharpen the focus of such an experiment, for example by forecasting the response variables, or to increase the efficacy of the seeding treatments, should precede any efforts to implement a randomized experiment. This also argues for numerical storm models that simulate realistic hailstone spectra for use in refining hail suppression concepts, a step that is well under way, but that needs stronger support.

These concepts, figure, and discussion represent the present state of hail suppression science. The stated concepts have been and are being used to guide operational 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 prime lessons for future operational hail suppression projects that has been learned from past projects is that the most effective seeding is done on the smaller, younger feeder cells

3.2 Cold season orographic cloud seeding programs

3.2.1 General discussion

Although there has been no fully randomized, completely observed chain-of-events, replicated, field experiment in winter cloud seeding, there have been a number of statistically oriented projects, some with thorough physical measurements, that yield considerable evidence of positive effects of cloud seeding (Gagin and Neumann, 1974; Elliott, 1986; Reynolds, 1988; Ryan and King, 1997). Notable examples are the Israeli I experiment, the Tasmanian operation, the Climax I and II projects (Grant, 1986; Mielke, 1995), the Lake Almanor experiment, and the Bridger Range experiment, these last two to be discussed below. The NRC report does an adequate job of discussing winter glaciogenic seeding, but leaves out a number of topics and references that, in our opinion, should have been included, particularly those concerning the chemical analysis techniques, which will be discussed later.

A number of observational and theoretical studies have suggested that there is a cold temperature `window' of opportunity for cloud seeding. Studies of both orographic and convective clouds have suggested that clouds colder than -25ºC have sufficiently large concentrations of natural ice crystals such that seeding can either have no effect or even reduce precipitation (Grant and Elliot, 1974; Grant, 1986; Gagin and Neumann, 1981; Gagin et al., 1985). It is possible that seeding such cold clouds could reduce precipitation by creating so many ice crystals that they compete for the limited supply of water vapor and result in numerous, slowly settling ice crystals which sublimate before reaching the ground. There are also indications that there is a warm temperature limit to seeding effectiveness (Gagin and Neumann, 1981; Grant and Elliott, 1974; Cooper and Lawson, 1984). This is believed to be due to the low efficiency of ice crystal production by silver iodide at temperatures greater than -4ºC, and to the slow rates of ice crystal vapor deposition growth at warm temperatures. Thus there appears to be a `temperature window' of about -5ºC to -25ºC where clouds respond favorably to silver iodide seeding (i.e., exhibit seedability). Dry ice (frozen carbon dioxide) seeding via aircraft extends this temperature window to temperatures just below 0ºC.

Orographic clouds are less susceptible to a `time window' as they are typically quasi-steady state clouds so they offer a greater time opportunity for successful precipitation enhancement than cumulus clouds. A time window of a different type does exist for orographic clouds which is related to the time it takes a parcel of air to condense to form supercooled liquid water and ascend to the mountain crest. If winds are weak, then there may be sufficient time for natural precipitation processes to occur efficiently. Stronger winds may not allow efficient natural precipitation processes but seeding may speed up precipitation formation. Even stronger winds may not provide enough time for even seeded ice crystals to grow to precipitation before being blown over the mountain crest and sublimating in the sinking subsaturated air to the lee of the mountain. A time window related to the ambient winds, however, is much easier to assess in a field setting for orographic clouds than for cumulus clouds.

Orographic clouds in the mountainous western states are often associated with passing synoptic scale storm systems. Wind flow over a mountain barrier causes the orographic lift to produce the cloud. Other types of clouds associated with frontal boundaries, convergence bands, and convective instability are also present during these storm systems, thus the orographic cloud scenario is often complicated by the dynamics of the storm system (changing winds, temperatures, and moisture).

It has been recognized for many years that achieving adequate transport and dispersion (T&D) of the commonly used ground-released silver iodide seeding agent is a key problem in seeding winter orographic clouds (Rangno, 1986; Reynolds, 1988; Super, 1990; Warburton et al., 1995a,b). Failure to document that clouds are actually being seeded continues to seriously hamper the development of this promising technology.

If SLW clouds upwind and over mountain barriers are routinely seeded to produce appropriate concentrations of seeding ice crystals, exceeding 10 to 20 per liter of cloudy air, snowfall increases can be anticipated in the presence or absence of natural snowfall. It has been repeatedly demonstrated with physical observations that sufficiently high concentrations of seeding agent, effective at prevailing SLW cloud temperatures, will produce snowfall when natural snowfall rates are negligible. Seeded snowfall rates are usually light, on the order of 1 mm/hr or less, consistent with median natural snowfall rates in the intermountain West (Super and Holroyd, 1997).

Weather modification scientists are well aware that AgI effectiveness is strongly dependent upon cloud temperature. Little physical (as opposed to statistical) evidence exists that AgI seeding has produced meaningful snowfall when treated SLW cloud temperatures were warmer than -8°C to -9°C except for the special case of forced condensation-freezing where seeding crystals may form near -6°C near the generators. But even in such special cases the crystals are carried to higher, colder SLW cloud regions. In order to be effective, the seeding material must be routinely transported into sufficiently cold SLW cloud and dispersed through large volumes of cloud, in sufficiently high concentrations. Both calculations and observations have shown that concentrations of effective artificial ice nuclei must exceed at least 10 per liter for detectable snowfall increases at the surface (Super and Boe, 1988; Super 1994; Holroyd and Super, 1998). The classic paper by Ludlam (1955) suggested that 10 to 100 seeding crystals per liter would be needed within cloud. Higher concentrations may be required for moderate seeded snowfall enhancement. For example, Super and Holroyd (1997) presented clear physical evidence of an AgI-seeded snowfall increase of 0.04 inches per hour (1.02 mm per hour) with an associated seeded ice crystal concentration of about 140 per liter. Median hourly snowfall rates are typically about half that rate at high elevations in the intermountain West.

3.2.2 Static seeding of winter orographic clouds

There are strong statistical suggestions of seeding effects from at least two randomized programs, the Lake Almanor Experiment (Mooney and Lunn, 1969) and the Bridger Range Experiment (BRE) as reported by Super and Heimbach (1983) and Super

(1986). Such suggestions from exploratory analyses should not be considered absolute proof by themselves. However, these particular experiments used high elevation AgI generators, a seeding approach which has been shown to routinely result in transport and dispersion of AgI plumes into the SLW zone. Moreover, both experiments have considerable supporting physical evidence in agreement with the statistical suggestions. Some physical evidence was collected during the BRE (Super, 1974; Super and Heimbach, 1983) and some later by cloud physics aircraft (Super and Heimbach, 1988). Convincing physical evidence, based on trace chemistry analysis of snowfall, was reported for the Lake Almanor target well after the randomized experiment, as reported by Chai et al. (1993) and Warburton et al. (1995a,b). The results of Warburton et al. (1995a) are in particularly good agreement with earlier statistical suggestions of seeding success with cold westerly flow, and further demonstrated that failure to produce positive statistical results with southerly flow cases was likely related to seeding affecting control stations (mis-targeting). Both experiments had evidence suggesting that the condensation-freezing mechanism resulted in the formation of high seeding crystal concentrations just downwind of the generators. This mechanism (Finnegan and Pitter, 1988) was not understood at the time of the experiments, but may have been a major factor in their promising results when AgI was released directly in-cloud at temperatures less than -6°C. Both experiments had evidence of the largest increases in snowfall within about 12 miles of the generators, and for colder cloud temperatures. The panel is unaware of other winter orographic randomized experiments from the western U.S. that have *both* strong statistical suggestions and considerable physical evidence to support those suggestions. According to the review by Reynolds (1988), only the Bridger Range Experiment had such dual evidence at that time.

These two randomized experiments strongly suggest that higher elevation seeding in mountainous terrain can produce meaningful *seasonal* snowfall increases. These suggestions are based on *both* statistical and physical evidence. Although the experiments were run decades ago, they are still worth reviewing in the absence of more or equally impressive results from the limited number of more recent randomized winter orographic cloud seeding experiments.

The studies of Warburton and Wetzel (1992), Warburton, et al. (1995a), and Super and Holroyd (1997) are pertinent. The Warburton and Wetzel paper showed how 8mm wavelength radar was used in conjunction with microwave radiometer measurements for assessing snowfall augmentation potential. The second paper reported on studies in Lake Almanor regarding the targeting and tracking of silver iodide in the precipitation which demonstrated that the transport and dispersion problems are significant and can lead to a much weakened capability of detecting seeding effects by precipitation statistics. The work of Super and Holroyd showed marked increases in ice particle concentrations produced by cloud seeding in Utah.

3.2.3 Additional research accomplishments; static seeding of winter orographic clouds

1) One of the most exciting accomplishments in recent snowpack augmentation research is the establishment of the direct link between the seeding activity and the water reaching the ground in the form of snow. The mm/hr increases in precipitation caused by silver iodide seeding have been documented several times in the reviewed scientific literature between 1988 and 1999. The link has been established by physical and chemical techniques. The snow precipitated at particular targeted sites is connected directly to the seeding material and to concurrently released chemical tracers in that snow. The big advantage of snowpack work is that the scientists are dealing with solid-state precipitation that can be sampled during and after storm events and stored in the frozen state until analyzed. The methodologies used to establish this direct linkage have been described by Warburton et al. (1985, 1994, and1995a,b) Super and Heimbach (1992), Chai et al. (1993), Stone and Huggins (1996), Super and Holroyd (1997), and McGurty (1999).

2) A second significant accomplishment in the snowpack augmentation studies provides a chemical explanation for the apparent failure of some larger scale randomized seeding experiments to achieve statistically significant increases in precipitation. Warburton et al. (1995b) have shown that, on the average, only 20% of the snow, which precipitated to the ground during the seeded periods of the Sierra Nevada Truckee-Tahoe project, showed evidence of being impacted by the silver iodide seeding. The results indicate that it would be necessary to produce very substantial changes in the limited areas where seeding material is detected, to yield a statistically acceptable change over the entire snowfall target area. Further studies of this type were conducted by Stone and Warburton (1989) in other Sierra Nevada regions seeded from ground-based aerosol generators.

3) Current physical and chemical evidence for these two significant accomplishments comes from research projects in the northern and southern Sierra Nevada and the Carson and Wasatch ranges of California, Nevada and Utah. Dual-channel microwave radiometers, short wavelength radars, ice-nuclei counters, sulfur hexafluoride gas and combinations of ice nucleating and non ice-nucleating aerosols (silver iodide and indium sesquioxide), have enabled scientists to identify the locations and the quantities of supercooled liquid water in winter storms and to track the seeding aerosols from their points of release to the targeted snowfall sites, as noted above.

4) The locations within winter storm clouds where ice-phase water capture occur have been studied by Warburton and DeFelice (1986) and by Warburton, et al. (1993). These studies and others in the Sierra Nevada and in the Australian Alps showed for the first time that the stable oxygen and hydrogen isotopic composition of ice-phase precipitation are related to the microphysical processes within the clouds in which the precipitation has formed. The work demonstrated that when orography dominated during the post-frontal storm period, the ice-phase water substance was being captured in the clouds between –5ºC and -14ºC with a peak around –11ºC temperature. This type of

information has been found very useful in the design of ground-based mountain area seeding projects.

5) Latest state-of-the-art remote sensing systems are a basic requirement for conducting successful snowpack augmentation programs. They can locate and measure in real time the distributions of cloud water and ice as well as wind flow patterns related to seeding aerosol transport. The wind profiler, the dual-channel microwave radiometer and the polarimetric radar have found substantial use in specific snowpack augmentation programs in Nevada, California, Utah and Arizona prior to 1995.

3.2.4 Additional evidence of wintertime cloud seeding effectiveness

There is a broad body of evidence in the literature and in company reports describing the results from various operational projects involving winter orographic clouds. Some projects in California have been in existence from the 1950's and 1960's. The Kings River project in southern California has been operational for 48 years and has produced an average 5.5% additional runoff per year (Henderson, 1986, 2003). An operational project run for the past 25 years or so in Utah has published results for 13 and 19 years of operations that indicate 11-15% increases in seasonal precipitation (Griffith et al., 1991; Griffith et al, 1997). Add to these results the San Joaquin River project showing at a minimum 8% increase in target area seasonal precipitation using trace chemistry studies of snowpack (McGurty, 1999), the Climax project indications of 10% increases, and the Tasmanian results of 10% increases in seasonal precipitation when storm cloud top temperatures are in the range of -10ºC to -12ºC and the evidence becomes very convincing that cloud seeding conducted under proper conditions increases precipitation in winter orographic situations. These findings and statements are in accord with the American Meteorological Society policy statement on weather modification regarding capabilities of winter orographic cloud seeding (AMS, 1998).

Most of the evaluations have utilized target-control regression techniques or snowcourse water content and precipitation storage data. Most of the evaluations of long-duration projects have provided evidence of increases in streamflow amounting to 5 to 10 percent of the natural flow (NRC 1966, 1973). More recent evaluations using precipitation or snow water content information have shown increases in the 10-15% range (Griffith et al., 1991). Conversion of these increases in precipitation into streamflow indicates increases in streamflow on the order of 10% (Stauffer, 2001). The consistency of results is encouraging.

Statisticians have questioned the validity of p-values obtained from sets of non-randomized data. Of particular concern is the fact that the seeded and non-seeded cases are drawn from different historical periods, instead of being interspersed in a random fashion. Gabriel and Petrondas (1983) have investigated this point with actual rainfall data, and confirmed that p-values from evaluations of non-randomized projects need to be adjusted for such effects, but not to the extent that the analyses are rendered invalid. Considering the hundreds of project-seasons of data that are now available, it appears that the latest NRC report should have confirmed, and even extended, the encouraging conclusions presented in previous reviews, rather than retreat to the position that it is premature to conduct operational projects.

3.2.5 Primary concerns in winter orographic programs

(a) Transport and Dispersion: One of the most significant uncertainties in larger scale seeding projects is the transport and dispersion of the seeding aerosols across the project areas. Results from several studies have revealed that most of the precipitation falling in the targets during seeded periods has not been impacted by the seeding process, assuming that the absence of the seeding chemical in the snowfall can be used for making such a deduction. New fully automated ground-based generators can be located in often not very accessible locations in the higher terrain of mountains thus reducing the problems of getting seeding materials into targets. Trace gases can also be used to track the seeding material through the target and if it occurs through the control areas.

(b) Remote Sensing: Although the wind profiler, the dual-channel microwave radiometer and the polarimetric radar and other short wavelength radars have found substantial use in specific snowpack programs prior to 1995, it is unfortunate that very few of these devices are available to the scientific or weather modification community outside of government agencies. There is a great need for resources and actual construction of such apparatus for new scientific research efforts.

(c) Statistical Analysis Methods: Because of the opportunity to shift the design of larger-scale seeding experiments to the use of physical and chemical assessment methods and to continue to satisfy the requirement of unbiased randomization, there is now a special need for new statistical approaches that are coupled with physical observations enabling comparisons to be made between those portions of the snowpack which have been impacted by the seeding during a seeding period and those which have not. For example, can snow samples that contain no seeding materials be considered as a ”no-seed” comparison set?

(d) Trace Chemical Facilities: It will be essential to ensure that adequate trace chemical laboratories are available for analyzing the snowfall for silver, indium, cesium and other tracer materials used in these snowpack augmentation studies. A few such laboratories do exist in the U.S. most of which have not been involved in weather modification.

(e) Environmental Impacts of Cloud Seeding Programs: Nearly all orographic weather modification programs in the western U.S. involve public lands. All agencies both governmental and private that engage in these weather modification programs are confronted from time to time by concerned citizens and environmental groups with questions about the environmental impacts of weather modification and the chemicals used in these programs. In cases where seeding aerosol generators are to be located on public lands, the land manager (e.g., U.S. Forest Service) is required to issue an environmental assessment and negative declaration prior to issuing special use permits for generator sites. Public agencies such as municipal utility districts, and state water agencies are often required to issue environmental assessment, environmental impact statements and declarations of negative impacts, to meet governing charters and law. These environmentally driven requirements involve much time and resources. Thus research on environmental impacts of weather modification programs and seeding agents is also a definite need. The development of a programmatic approach in this area could be very beneficial.

(f) Seeding Agent Chemistry and Improvements in Delivery Systems: Modern formulations of seeding chemicals can start producing significant numbers (10^{12} particles per gram of active agent) of effective ice nucleation at temperatures colder than about -4ºC. However, winter orographic clouds in much of the western U.S. have significant amounts of time when there is SLW at temperatures in the 0ºC to – 4ºC range. Can improvements be made in the seeding chemistry to achieve effective ice nucleation at these warmer temperatures? Ground-based seeding aerosol generator designs have been improving in recent years toward more reliable remote operation. Optimization of atomization, flame temperatures, flow volumes, power consumption and data telemetry are areas recommended for continuing improvements.

3.2.6 Watershed experiment

The BASC Workshop report (BASC, 2001) included a strong recommendation that a "Watershed Experiment" be conducted in the mountainous West using all of the available technology and equipment which can be brought to bear on a particular region which is water short and politically visible from this water-short viewpoint. The NRC report did not include this recommendation, but this response re-introduces this recommendation. The "Watershed-sized Project" should be designed to demonstrate that snowfall could be augmented over a watershed using scientifically acceptable statistical and physical measurement strategies. The methodology should include following the hypothesized "chain-of-events" using airborne and remote sensing technologies. Model forecasts and remote sensors should be used to determine optimum positioning of ground-based generators and the optimum times for their operation. The investigations should include evaluations of snowpack melting, run-off, stream flow and recharge of ground water aquifers. In addition, it should include environmental impact studies within the region, including water quality, stream flow standards and protection of endangered species, while at the same time satisfying the overall water requirements of the inhabitants of the watershed such as Native Americans, ranchers, farmers, residents of local townships and industry.

There are several western states watersheds that are worthy of consideration for such a program. One of these would encompass portions of the McCloud River and Pit River basins of northern California. This watershed covers approximately 800 square miles, offers high elevation terrain extending from Mt Shasta (14,000 ft. elevation) eastward for approximately 40 miles, by southward approximately 20 miles, and produces more than 1 million acre-ft of water annually. This area is relatively isolated from other weather modification programs. Pacific Gas and Electric (PG&E) is considering implementing a weather modification program in this region. PG&E calls this "The Upper McCloud and Lower Pit River Aquifer Recharge Program", and the intent would be to maintain and increase long-term hydrostatic pressure in the aquifers, which supply sustained base flows that continue into and through California's frequent dry years. Potential direct beneficiaries of a program in this basin include the 4 million electric customers of Pacific Gas and Electric (PG&E) Company, and the 32 million citizens of California (McCloud-Pit Rivers are main tributaries that feed USBR's Lake Shasta and this is one of the largest water supplies for agriculture and public uses in California). Such a research program could potentially leverage financial resources and technical expertise from PG&E, from the state of California, from the USBR, and from Atmospheric Sciences departments at a number of universities in California, Nevada and Oregon

A second candidate for the watershed study is the Walker Rivers catchment areas of the Sierra Nevada. This would also be an excellent choice for such a watershed experiment, having a catchment area of 1200 square miles at elevations above the snowline of 6000 ft. They contain two principal rivers feeding substantial ranching and farming activities, three townships, and terminating in a desert lake downstream of an Indian reservation.

The McCloud-Pit and Walker watershed candidates are offered here as examples and not as the final candidate list. Other suitable watersheds exist in western states, including Utah, Colorado and Idaho. An ultimate selection would be determined based on many factors, including proximity to nearby projects, that matrix toward achieving a program of greatest value.

This review panel recommends that a "Watershed Experiment", fully randomized and well equipped, be conducted in one of these regions of the mountainous, water-threatened West, because it will benefit substantial segments of the community, including Native Americans, urban water users, ranching, and farming communities, and recreation interests.

3.3 Summer operational programs

The NRC report (p 68) touts the potential for hygroscopic seeding of warm season convective clouds, and encourages further investigations in this area. While we agree that considerable potential does exist for hygroscopic seeding, we do not agree with the NRC finding regarding glaciogenic seeding that there " is recognition of the lack of credible scientific evidence that applying these concepts will lead to predictable, detectable, and verifiable results." There are many situations in which hygroscopic seeding is not feasible, and we believe that glaciogenic seeding still has much to offer, even though more complete evidence of cause and effect is desirable.

Progress has been made. For example, the initial objective of weather modification research work in Texas focused on formulating a conceptual model for rain enhancement. The High Plains Experiment (HIPLEX) sponsored by the U.S. Bureau of Reclamation, and based in Big Spring from 1975-1980, led to the identification of experimental units, seeding hypotheses, covariates, and response variables for subsequent fieldwork conducted a decade later as part of the NOAA Atmospheric Modification Program (AMP), discussed below. The Texas HIPLEX led to the conclusion that seeding for dynamic effects may have substantial impact on convective cloud clusters, deemed to be the most favorable candidates for the "experimental units" in subsequent exploratory research (Riggio et al., 1984). While precipitation is often initiated in west Texas clouds through the warm rain process, the ice phase was observed to dominate during much of the subsequent cloud development, with the rapid development of greater ice particle concentrations being a consequence of an active ice multiplication process. With radar observations of merging cloud echoes, particularly clusters, suggesting an interaction between individual convective towers with the mesoscale systems, it was deduced that additional cloud growth could be facilitated through the seeding of turret clusters.

Additional field work, consisting of the collection of 34 experimental units over a number of weeks during four summers in the latter half of the 1980s, led to refinement of the seeding conceptual model. Randomization of the seeding allowed comparisons to be made between the behavior of treated and unseeded convective 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 on average 36 percent longer than their untreated counterparts, expanded to produce rainwater over an area 43 percent larger, and tended to merge with adjacent convective cells nearly twice as often. Intriguingly, the seeded clouds grew only marginally taller (about 7 percent) than the unseeded ones. (Both rainfall and merger statistics were significant at better than the 5 percent significance level.) These results confirm earlier results from the Dakotas (Dennis et al., 1975) that show broader and longer lasting echoes from the seeded cells in that region. In addition, the extra growth in height in the seeded clouds was an average 600 m, or less than 10% of the cloud depth. These last authors commented on the fact that both dynamical and microphysical changes appeared to be important in producing the increases in rainfall from the seeded cells.

With a new conceptual model suggesting seeding for dynamic effect can also produce a substantial increase in rainfall without causing a sizeable increase in the maximum height of the seeded cloud (Rosenfeld and Woodley, 1993), further research in Texas in the 1990s documented the physical processes operative within the vigorous supercooled convective towers at the time of treatment with glaciogenic material. In addition to finding that the internal cloud structure is strongly dependent upon cloud base temperature, evidence was produced strongly suggesting seeding works well in clouds having an abundance of supercooled water, especially where such water in a vigorous, supercooled updraft region is available for artificial nucleants having a greater cross-sectional area for accretion of cloud water (Rosenfeld and Woodley, 1997). It was also observed that the time to reduce the maximum amount of cloud water in seeded convective towers to half of its initial value was lessened by some 2 to 3 minutes from that in the unseeded cases.

Additional exploratory research in the Montana HIPLEX (1975-1980), and later in North Dakota (1987-1993) further examined the precipitation processes in cumuliform clouds. In the North Dakota work, many of the new technologies cited in the NRC report were applied. In addition to the tracer techniques cited in the brief review of the NOAA Atmospheric Modification Program (AMP) elsewhere in this response, the North Dakota researchers used dual-channel microwave radiometers, in situ cloud microphysical measurements, including within hailstorms themselves (Detwiler et al., 1994a, b), and numerical cloud models. Some of the modeling was done in real-time, for predictive purposes, much else was done *post hoc*, to gain a better understanding of the observations made, and to allow further improvements to the models. These modeling efforts are also discussed elsewhere within this response.

Our point here is two-fold. First, contrary to the implications of the NRC report, there has been quality research in conjunctions with ongoing operational programs published in the refereed literature. Secondly, the research ceased only when federal involvement at a significant scale ended. We wholeheartedly endorse the NRC recommendation that a renewed long-term research effort be undertaken, and agree that a number of critical issues remain to be fully answered.

We also maintain that coupling physical experiments with ongoing operational programs for exploratory experiments would be a productive, cost-effective approach to answering many of the questions posed in the NRC report. We acknowledge, however, that only conducting randomization apart from existing operational programs will afford the strength of statistical design necessary for confirmatory experiments.

3.4 Cloud modeling of cloud seeding effects

This has been a continuing effort conducted by a few cloud modeling groups over the past thirty years. Simulations of many types of cloud seeding experiments have been accomplished. Much of the work depended on simplifications of the microphysics and of the dynamics, but even so basic effects were evident that will likely stand the test of more sophisticated treatments suggested in the NRC report. Some of the findings are listed below.

The NRC report failed to critically review the development of cloud models over the past 20 to 30 years, with respect to cloud seeding simulations, and with respect to natural cloud precipitation simulations. No NRC committee member was particularly active in the modeling field, except in the dynamics of clouds. The report concentrated on the future use of complex microphysical and three-dimensional, time-dependent research cloud models that in general are of little use in operations now. They failed to evaluate what has been developed and what could be applied with current computer power and model capabilities on operational projects.

Bulk-water microphysical techniques were used in most of the cloud models in the early days and are currently being used in large-scale weather prediction models. This process, assumes zero terminal velocity for the cloud water and cloud ice, relatively small terminal velocities for snow content, modest values for rain, and the largest vertical velocities for graupel and hail. The velocities vary with the quantity of precipitation content at a grid point. Such a framework allows for the production of rain from cloud water, the formation of cloud ice at appropriate observed temperatures, the production of snow from supercooled water and cloud ice or the depositional growth of cloud ice, and the production of graupel/hail from frozen rain (via probabilistic freezing) or interactions between the liquid and ice contents. If rain does not form from cloud liquid (as is the case in many higher latitude clouds) then it forms later in the lifetime of the cloud through melting of ice particles. The growth of the graupel/hail considers both wet and dry growth processes. Nearly thirty interactive processes among the various water processes (such as accretion, collection, aggregation, etc.) are simulated. The paper by Lin et al. (1983) describes the early development that is the basis for many of the models.

It has become more common in recent years for bulk microphysics schemes to predict two moments such as hydrometeor mixing ratio and concentration (Ferrier et al., 1995; Meyers et al., 1997; Reisner et al., 1998). A somewhat different paradigm is to emulate an explicit bin model by prescribing basis functions for the drop size distributions such as gamma or log-normal distributions (Clark, 1976; Clark and Hall, 1983) and explicitly predict the evolution of those basis functions by vapor deposition/evaporation, stochastic coalescence, and sedimentation. Tzivion et al. (1994) predict three parameters that fully define the basis functions: mixing ratio, number concentration, and a third moment. Milbrandt and Yau (2004) have implemented such a model for application to hailstorm simulations. This model does a much better job of representing hail processes than the earlier bulk-water microphysical methods without the expense of a full-bin-resolving model and can readily be implemented in three-dimensional storm models.

To better model the precipitating ice, Farley developed a hybrid method that utilizes twenty categories (now twenty-one), or bins, for these particles. The sizes range in diameter from 100 µm to 5.0 cm (recently increased to 7.0 cm by adding the extra bin). Bulk-water microphysical methods are used for the cloud liquid, cloud ice and rain fields, hence the hybrid terminology. The dynamic framework for the microphysics has been a two-dimensional, time-dependent cloud model and a three-dimensional, time-dependent, cloud-resolving mesoscale model developed by Clark (1977, 1979), Clark and Farley (1984) and Clark and Hall (1991). The IAS two-dimensional framework has been used to simulate hail formation and fallout in an Alberta hailstorm (Farley, 1987) in both seeded and unseeded conditions, and in a North Dakota hailstorm (Farley et al., 1996, 2004a,b). Good agreement with radar observations was obtained in the Alberta and North Dakota hailstorms. This model framework allows the type of hailstone embryos, either frozen raindrop or graupel, to be identified (Kubesh et al., 1988). A critical component of the Kubesh study was the data provided by the armored T-28 aircraft involving particles types and sizes inside the strong updrafts of a supercell storm. Both model and observations indicated the importance of shedding from graupel and hail particles to produce rain for fallout and for hailstone embryos in the rich supercooled liquid water environment.

In addition, the three-dimensional Clark model has been used to simulate snow and rainfall over the Black Hills of South Dakota and Wyoming (Farley et al., 2000) during a four-day storm period. Simulation of the cold precipitation period produced reasonably accurate precipitation patterns, but not as accurate for the warmer, weakly forced situation. This last result indicated that a simulation of a drizzle process should improve the rainfall comparisons, as was also called for in the NRC report. A simulation of ground-generator cloud seeding of the storm system was reported in Farley et al. (1997), which showed that the cloud seeding was effective on only one of the four days. Other orographic simulations of precipitation formation and the effects of cloud seeding are found in Meyers et al. (1992, 1995).

Some success has also been obtained in the three-dimensional modeling of convective clouds and storms. The 3D cloud-resolving model of Clark (with the bin ice microphysics of Farley) has been used to simulate hailfall in northern Italy (Wobruck et al., 2000) and in southern France (Wobruck et al., 2003). This last study showed good agreement with observations of the hailstone spectrum at the ground. Johnson et al., (1993) simulated the 2 August 1981 CCOPE supercell with both liquid water microphysics (LWM) only and with a hail category version (HCM) of the model (similar to the hail formulation of Farley). The ice microphysics was shown to be important for the better comparison with the actual storm, but the LWM simulation reproduced some of the important dynamics of the supercell storm. The T-28 armored aircraft provided critical information from inside the storm that was used for the comparisons. Farley et al. (1992) used the 3D Clark model with bulk-water microphysics to simulate a moderate size rain shower in the CCOPE field study. Several characteristics of the actual storm were captured in the simulation.

A three-dimensional framework is preferable, but sometimes not practical. The two-dimensional cloud models have been tested in several WMO workshops (WMO, 1985, 1988, 1994) and reported in the literature (Tuttle et al., 1989; Helsdon and Farley, 1987a; Hjelmfelt et al., 1989). The models simulated satisfactorily many of the characteristics of cloud and storm systems, including the development of realistic radar signatures and the production of microbursts. Their greatest disadvantage is the too rapid development of rain from coalescence of the cloud water in the bulk-water models. (This is more of a concern in weaker cloud situations than in strong, convective continental type clouds where the ice processes dominate and rain forms predominantly from the melting of graupel or hail.) Their advantage over one-dimensional models is that they simulate realistic airflows and water contents to produce reasonable simulations of rain or hail in the cloud and fallout at the ground. They can and have been used in real-time forecasting to analyze the potential of an atmospheric sounding to support the production of precipitation (Tuttle et al., 1989; Kopp and Orville, 1994). This was done during the NDTP in 1989, and to a lesser extent in the NDTE in 1993.

Separate from these microphysical discussions is the fact that the cloud modeling of the past two to three decades has indicated the importance of including the effects of larger scale convergence and the heating and evaporation at the earth’s surface in the simulations (Chen and Orville, 1980). Observations and modeling results indicate that convergence or divergence values of order 10^{-5} s^{-1} may affect significantly the degree of cloud development and should be included in models trying to predict or simulate real clouds. The convergence has an effect on the frequency of cloud merger. Similarly, the inclusion of reasonable heating and evaporation rates at the ground can be very important to the amount of rainfall predicted. Thus there are many things in addition to the microphysics that should be considered to produce realistic predictions and simulations of clouds and storm systems.

<u>Atmospheric electricity modeling.</u> The NRC report speculated about the possible influence of atmospheric electricity in natural precipitation and in cloud seeding results. Helsdon and Farley (1987b) published the first simulation, including atmospheric electricity effects, of a cloud that produced lightning. Further work has advanced to simulations in the 3D Clark/Farley model that include the actual simulation of the lightning flashes in the storms and more refined atmospheric electricity modeling (Helsdon et al., 1992, 2001, 2002; Zhang, et al., 2003). The models are too complicated for real-time application in cloud seeding operations at this time. Bulk-water microphysics has been used to develop the theory.

Following are some of the findings and predictions from cloud models employing realistic cloud seeding and storm simulations. Background material for most of the statements can be found in Orville (1996) and in the references listed therein.

Convective-type Clouds (cumulus congestus to cumulonimbus)

a) Dynamic seeding effects have been simulated, primarily the increased updrafts associated with the freezing of supercooled liquid water. Of particular importance here was the demonstration that near instantaneous freezing of the supercooled water was not possible (but had been used in the one-dimensional, steady-state cloud models). Much of the latent heat of freezing is released over the period of a few minutes by the accretion of the supercooled water by larger ice particles.

b) Microphysical or “static” seeding effects have also been simulated; they show an effect on the cloud and environmental airflow and emphasize that static seeding has dynamic effects. The primary effect here is the early fallout of the seeded precipitation and the generation of new cloud cells. Downdrafts in the cloud and in the subcloud layer are affected.

c) The interactions of the precipitation with the internal circulations of the seeded cloud and the environmental airflow are often crucial to the total precipitation from a cloud and cloud system.

d) Greater seeding effects occur in moderate size convective clouds (cloud depths in the 3 to 7 km range, tops -10º C to -25ºC). The one-dimensional cloud models have been key in demonstrating this feature. Field studies in Cuba and in Texas have also shown such effects (Koloskov et al., 1996; Rosenfeld and Woodley, 1993).

Stratiform-type Clouds (often orographic clouds)

e) “Dry” as well as “wet” clouds may respond to dynamic seeding, yielding more vigorous circulations in the cloud and greater precipitation on the ground. This is caused by the transformation of the heavily seeded cloud region to saturation with respect to ice instead of saturation with respect to liquid water (Orville et al., 1984, 1987). The production of embedded cells in orographic upslope airflow may be caused in some instances by these effects.

f) The “Goldie-locks” effect is evident, i.e., some conditions are too warm, some too cold, and some just right for ice-phase seeding to be effective.

g) Transport of the seeding material to proper parts of the clouds may not be possible in some situations, but may be predictable by cloud-resolving mesoscale models that include conservation equations for the seeding agent.

Hailstorms

h) Hailstone spectra within the storm are being simulated and the effects of seeding modeled. Observations of hailfall at the ground appear reasonably similar to that predicted in an unseeded case.

i) Hailstorm cells with an active coalescence process react more positively to ice-phase seeding than do more continental-type cloud cells, in some situations.

j) The location of favorable regions for hail embryos that produce the larger hail can be identified.

k) The type of embryo, rather frozen rain or graupel, can be identified, and the proportion of each that are used to produce hailstones.

l) The importance of shedding from graupel and hail to produce rain is demonstrated.

General Results

m) Seeding agents (such as silver iodide and hygroscopic material) and dry ice seeding have been simulated in cloud models. Conservation equations need to be used for the seeding methods instead of making arbitrary decisions as to when and where to change the ice crystal concentrations.

n) The seeding material generally affects only restricted portions of the clouds.

o) Hygroscopic seeding affects the coalescence process, and accelerates the glaciation of the cloud. Consequently, hygroscopic seeding has the very real possibility of providing both warm rain and cold rain modification effects.

p) Redistribution of the precipitation occurs in some of the seeding simulations. Whether this occurs or persists over the duration of a field project needs to be determined by observations and additional mesoscale simulations.

q) The amount of precipitation simulated or predicted by cloud models depends sometimes on the proper amount of larger scale convergence and/or surface heating and evaporation prescribed in the models, which can be obtained by observations.

r) Cloud particle initiation processes, although extremely small in magnitude, need to be retained in the model microphysical equations. Otherwise, the critical paths to precipitation (either liquid or ice) will not be captured correctly.

These results have come from cloud models of varying complexity. The grid resolution is relatively fine, normally 100 to a few hundred meters. Bulk-water microphysics is used to produce most of the results, although bin microphysics is being used for the precipitating ice in the hail models (and is necessary for the prediction of cloud seeding effects on hail spectra). Such models could be used to help in operational cloud seeding projects, identifying those days that might be more susceptible to cloud seeding attempts. Moderate computing power could provide near real-time results. The NRC report is short on a discussion of possible modeling support for operational projects.

The NRC report emphasizes the use of bin microphysics in three-dimensional, time-dependent cloud and mesoscale models. The report takes little note of the development of simpler models and simpler domains. The fact that there are unknown parameters in the bin models means that there are possibly hundreds of interactions that will be affected. This argues for the development of bulk-water microphysical models that have far fewer unknown parameters. The bin-microphysical models will be very useful in developing the best parameterizations for the bulk-water microphysical models. Climate change theory would have progressed very slowly if only the most complete and complex models had been accepted. Every thing from one-dimensional to three-dimensional models has been used. The same needs to be done in weather modification, and particularly in the support of operational projects.

4 Additional Topics and Other Modifications to the NRC Report

4.1 The NOAA Atmospheric Modification Program

The NRC report stated that very little research had been done on operational programs. From 1986 through 1995, the NOAA Federal-State Atmospheric Modification Program (AMP) funded weather modification research, first in Illinois, Nevada, North Dakota, and Utah, and in the latter years, also Arizona and Texas. This funding, on average about $500K per year per state (2 to 3 million dollars per year), was used to bring research components to ongoing operational cloud seeding programs in these states. Federal funds were never used to conduct any actual seeding, but allowed radars, radiometers, instrumented aircraft, and other physical and scientific (human) resources to be focused on those issues deemed to be of greatest concern. Three of the states, North Dakota, Illinois, and Texas, focused their available resources on warm season weather modification research. The other three focused their efforts on wintertime orographic cloud seeding.

The executive summary of the NRC reports notes that, "Advances in observational, computational, and statistical technologies have been made over the past two to three decades that could be applied to weather modification." During the AMP, when funding *was* available, many of these technologies *were* brought to bear. North Dakota was able, with NOAA and NSF support, to field two significant field programs. The first, in 1989, was the North Dakota Thunderstorm Project (NDTP), and included the deployment of NCAR CP-3 and CP-4 C-band Doppler radars, the NOAA-ETL X-band circular-polarized Doppler radar, and instrumented aircraft from the University of North Dakota, the University of Wyoming, the South Dakota School of Mines and Technology, and the NCAR Sabreliner (Boe et al., 1992). A NOAA WP-3D "Hurricane Hunter", and a tracer release aircraft provided by Weather Modification, Inc. augmented these aircraft. A similar but smaller scale program was conducted in 1993 (Boe, 1994), the North Dakota Tracer Experiment (NDTE, referenced only briefly by the NRC report).

Both of these programs utilized Doppler radars, in situ cloud sampling, numerical modeling (see Section 3.4), and atmospheric tracers (chaff and sulfur hexafluoride) to study the transport and dispersion with actively growing convective cloud turrets, and established unambiguous linkages between seeding with glaciogenic agents and the subsequent cloud glaciation (e.g. Detwiler et al., 1994a,b; Huston et al., 1991; Martner et al., 1992; Reinking and Martner, 1996; Stith et al., 1996; Stith et al., 1993; and Stith et al., 1990). Figure 4.3 of the NRC report is from this research in North Dakota (Reinking and Martner, 1996), but the NRC report does not acknowledge it as having been weather modification research. This is not to say that this work is completed; to the contrary, only the first steps have been taken.

The other states experienced similar successes. Some of the initial funding obtained under this program was used to build two new dual wavelength microwave radiometers and one short wavelength radar for use in the research programs in Utah, and Nevada. These research funds were also partly used for upgrading the trace chemical analysis facilities in Nevada. The research results obtained from these financial expenditures are described in a substantial number of publications listed at the end of the sections of this critique describing the research activities on snowpack augmentation orographic programs in Utah, Nevada and California.

The breadth of the various research efforts and list of all resulting publications is far too lengthy to include here. All of the programs utilizing these new tools were studying operations or processes directly related to operations, so the NRC report assertion that little research has been done on operational programs in recent years is less than accurate, except perhaps for the period since the AMP was terminated in the later 1990s. It is worth noting that papers from AMP era field efforts are still being published; e.g., Farley et al. (2004a, b).

Funding for the AMP was terminated along with many other programs in the NOAA budget after changes in congressional leadership following the 1994 elections. Some federal funding has been re-established in 2003 and is being administered by the USBR.

4.2 Other items

The NRC panel provided an excellent summary of existing technology that can be applied to the measurements of clouds. They described several in situ measuring devices for cloud particles, updraft velocities, water contents and other devices, but then failed to note that the observations normally require in-flight penetrations of the clouds and storms. The discussion and references above show the valuable observations acquired by the armored T-28 aircraft. Certainly, that type of capability should be maintained in the future to make the critical measurements needed in both seeded and natural cloud environments.

The NRC panel missed an opportunity to support an example of innovative evaluation of an operational project. The Woodley/Rosenfeld radar evaluation of a Texas program is being published soon (Woodley and Rosenfeld, 2004), but was available earlier to the panel. The technique uses radar estimates of rainfall (checked against rain gauges) in both target and surrounding area to estimate the cloud seeding effect in the target areas. Selection of control cases is done entirely objectively. The apparent effect of seeding was very large. The most conservative and credible estimates of seeding effects were obtained from control matches drawn from outside the operational target within two hours of the time that each unit was seeded initially. Under those circumstances, the percentage increase exceeded 50% and the volumetric increment was greater than 3000 acre-feet (3700 kilotons) per target unit. It is regrettable that several lay persons and two meteorologists (neither with any cloud seeding experience) were able to convince the public that the drought conditions they had been experiencing were due to negative cloud seeding effects and to close that project for the remainder of the 2002 season and in 2003.

The NRC panel should have recognized that much of the work they recommend could be helped by the conscious use of cloud seeding agents, but instead they advised researchers to stay away from applications. When researchers have agents that can change the microstructure of clouds, the use of them during research projects can indicate whether they understand the natural processes.

We are concerned with the NRC's procedure in the course of such a difficult review process. Only two of the nine committee members had extensive weather modification experience, none in hail suppression. Some had excellent backgrounds in technologies used in weather modification. The committee cited the extent of their interaction with the "community" and listed those participating in one of the report appendices. A few of us on this WMA committee were listed in that community. Our personal experience and those of at least one other modeler listed is that, in some instances, the contact was of the briefest kind, perhaps a phone call to obtain a reference or a passing conversation in the hall at work. Consequently, the appearance of broad community participation in the NRC report is exaggerated.

4.3 Additional WMA perspectives on cloud seeding technology

Despite the difficulty in objectively quantifying the absolute values of seeding effects, the large body of positive indications reported by many (see, for example, Todd and Howell (1985)) and other references in this report, and a multitude of analyses in the literature constitute a collective positive signal. Objective consideration of the entire body of evidence, ranging from *a-posteriori* analyses in operational project reports to carefully designed and conducted research-oriented operations and analyses leads us to the conclusion that cloud seeding, when properly conducted, can, in appropriate atmospheric conditions, have a positive effect on precipitation. This position is supported by one of the observations of the NRC report noting an increase in operational cloud seeding programs in many parts of the world in recent years with a dramatic decrease in research funding for such programs. However, we would recommend that research be strengthened to help evaluate and optimize the operational programs.

The sponsorship decision to support an operational cloud seeding program can perhaps best be viewed as a risk management assessment. What is the risk of making the wrong decision weighed against the potential benefit/cost ratio? Numerous studies have demonstrated that a 10-15% increase in precipitation can provide sizable benefits to a variety of beneficiaries (irrigated agriculture, hydroelectric production, municipal water supplies) at very favorable benefit cost ratios of 5-10/1 or higher. For example, if a potential sponsor of a cloud seeding program, following careful deliberation, decided they had an 80% likelihood of obtaining a 10% increase in precipitation that would yield a benefit/cost ratio of 10/1, they would probably chose to support the program.

The other part of the dynamic driving the increase in operational programs, especially those involving precipitation enhancement, is related to increasing populations and either stable or declining (pollution, drought, depletion of ground water, etc.) water supplies. This factor, coupled with the relative ease with which cloud seeding programs can be designed, implemented and operated and stopped without long term commitments and large capital investments make cloud seeding a very attractive alternative for water managers to consider. In addition, existing storage facilities, pipelines, and canals can be used to store and distribute additional water produced through cloud seeding at little or no additional cost.

Given that the number of operational programs will likely continue to increase with time we urge that modern advancements in equipment and seeding strategies be used on operational projects and that independent evaluations be performed, whenever possible.

Additional information on the capabilities of planned weather modification technology can found at WMA's website, http://www.weathermodification.org/facts.htm.

5. Conclusions and Recommendations

The WMA has responded to the NRC report concerning issues having operational impact or scientific consequences on operational projects. The WMA strongly supports the NRC's recommendation to establish critical randomized, statistical experiments along with the necessary physical measurements and modeling support to reduce the many uncertainties that exist in the science of weather modification.

The NRC panel conclusion that there was no convincing scientific proof that cloud seeding has worked (with a few exceptions), applied a definition of scientific proof that few atmospheric problems could satisfy. On the other hand, the NRC panel concluded, "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". Differing levels of proof have been applied by NRC panel to planned weather modification versus global climate change and inadvertent weather modification. A "higher bar" criterion was applied to planned weather modification.

The NRC panel cited a much earlier NRC report (NRC, 1964) and concluded that the initiation of large-scale operational weather modification would be premature. We think that it is inappropriate for a national academy panel, with very limited operational weather modification experience, to make such a judgment. Citation of the very dated 1964 report suggests that little has changed since that time. The NRC panel notes operational programs in 24 countries and at least 66 large-scale operational weather modification programs in the U.S. The WMA believes large-scale operational programs have produced and continue to produce positive effects for society. The WMA does not agree with the NRC suggestion that implementation of large-scale operational programs would be premature. WMA's response details many examples of successful operational programs, and provides information on the myriad of technological advances that have been made, but that were largely neglected by the current NRC report.

This WMA report has added information on hail suppression, winter orographic cloud seeding, summer operational programs, and cloud modeling of cloud seeding effects to fill in for gaps and weaknesses in the NRC report. A few other topics are also commented upon. We support many of the recommendations of the NRC panel, but add several of our own as follows:

- We support the NRC recommendation that there be a renewed commitment to advancing our knowledge of fundamental processes that are central to the issues of intentional and inadvertent weather modification.

- We support the NRC recommendation that a coordinated national program be developed to conduct a sustained research effort in the areas of cloud and precipitation physics, cloud dynamics, cloud modeling, laboratory studies, and field measurements designed to reduce the key uncertainties that impede progress and understanding of intentional and inadvertent weather modification. *But, we argue that the coordinated national program should also support exploratory and confirmatory field studies of in weather modification. It should capitalize on operational cloud seeding programs, and use them as a basis for testing models, and developing new statistical methods for the evaluating the efficacy of those operations.*

- We support the NRC conclusion that a coordinated research program should capitalize on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems

- The BASC 2001 workshop report recommended that a "Watershed Experiment" be conducted in the mountainous West using all of the available technology and equipment that can be brought to bear on a particular region which is water short and politically visible from a water resource management perspective. We strongly support this earlier recommendation that was not in the NRC report. Such a "Watershed Experiment" should be fully randomized and well equipped, and be conducted in the region of the mountainous West of the U.S. where enhanced precipitation will benefit substantial segments of the community, including enhancing water supplies in over-subscribed 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 and remote sensing technologies, along with trace chemistry analysis of snowfall from the target area. Model simulations should be used to determine optimum positioning and times of operation for ground-based and aircraft seeding. The work should include evaluations of precipitation, run-off, and recharge of ground water aquifers. Also, it should include environmental impact studies including water quality, hazard evaluations such as avalanches, stream flow 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.

- We recommend the application of existing and newly developed numerical models that explicitly predict transport and dispersion of cloud seeding agents and activation of cloud condensation nuclei, giant cloud condensation nuclei, and ice nuclei, as well as condensation/evaporation and collection processes in detail, to the simulation of modification of clouds. We concur with the need to improve and refine models of cloud processes, but existing models can be used as a first step to examine, for example, the possible physical responses to hygroscopic seeding that occur several hours following the cessation of seeding. In addition, existing models can be used to replicate the transport and dispersion of ground-based and aircraft-released seeding agents and the cloud and precipitation responses to those seeding materials in winter orographic clouds. Existing models can also simulate static and dynamic seeding concepts for fields of supercooled convective clouds. Moreover, existing models can be used to improve the efficiency of the operation of weather modification research projects and operational programs, and be deployed in the assessment of those programs.

- We recommend that a wide range of cloud and mesoscale models be applied in weather modification research and operations. This includes various microphysical techniques (both bin and bulk-microphysical models have their uses) and various approaches in the dynamics (all dimensionalities - one, two, and three dimensional models - offer applications). The application of hybrid microphysical models should be especially useful in simulating hailstorms and examining various hypotheses and strategies for hail suppression.

- We recommend that a concerted effort be made in the field and through numerical modeling, which includes simulations of hailstone spectra, to study hailstorms and the evolution of damaging hailstones as well as examine potential impacts of modified hailstone spectra on the severity of storms. Because operational programs regarding hailstorms are currently being conducted in the U. S., we encourage the "piggybacking" of research on such projects. We also encourage active cooperation with international hailstorm projects to elicit data and information concerning suppression concepts and technology.

- We recommend that an instrumented armored-aircraft capability (storm penetration aircraft, or SPA) be maintained in the cloud physics and weather modification community. This is essential for the in situ measurements of severe storm characteristics and for providing a platform for some of the new instruments described in the NRC report.

- We recommend that support be given for the development of innovative ways to evaluate operational cloud seeding projects. This is particularly important for the establishment of the physical basis of various cloud seeding methods and for establishing the possible range of cloud seeding effects.

- We recommend that evaluation techniques presently being applied to operational programs be independently reviewed, and as necessary revised to reduce biases and increase statistical robustness to the extent possible. Recognizing that randomization is not considered to be a viable option for most operational seeding programs, we acknowledge that there is much room for improvement in most present evaluations, many of which are presently done in-house.

- We recognize that much of the cloud seeding conducted today, and likely in the future, is done in situ by aircraft. A limited weather modification pilot training curriculum presently is in place at the University of North Dakota (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 IMC (instrument meteorological conditions) and including actual hands-on, in-the-cockpit seeding experience. Correct targeting is mission-critical, yet many pilots presently working on operational programs receive only limited training, many not having the benefit of any formal training whatsoever. When pilots are undertrained, project results are likely to suffer. A certification program for pilots by an organization such as the WMA, which, in addition to formal university instruction might include periodic recertification and/or recurrency training, would significantly improve the overall abilities and capabilities of the operational weather modification pilots.

We encourage the scientific and operational communities in weather modification to cooperate and work together whenever and wherever possible to solve the many problems slowing progress in the field. The future should not involve solely operational programs or research efforts. The two should be coupled whenever possible, to work together toward the many common goals.

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7. Appendix Committee Member Biographies

Mr. Bruce Boe Mr. Boe has worked with clouds, cloud physics, radar, and aircraft since 1974, and has logged hundreds of hours in aircraft studying thunderstorms and winter storms over much of the western U.S. Prior to assuming his present position as Director of Meteorology for Weather Modification, Inc., he was for 12 years Director of the North Dakota Atmospheric Resource Board, a division of the State Water Commission, and previously worked for the University of Wyoming, the U.S. Bureau of Reclamation, and the State of Montana. He is an active member and past president of the Weather Modification Association, presently serving as Association Webmaster. He is a member of the American Meteorological Society, and past chair of the Society's Committee on Planned and Inadvertent Weather Modification. He is an affiliate member of the American Society of Civil Engineering (ASCE). Bruce was Principal Scientist for the State of North Dakota in the National Oceanic and Atmospheric Administration's (NOAA's) Atmospheric Modification Research Program, and coordinated two significant thunderstorm research programs: the North Dakota Thunderstorm Project (1989), and the North Dakota Tracer Experiment (1993).

Mr. George Bomar Mr. Bomar has devoted nearly 30 years in State of Texas service toward the development and implementation of weather modification technologies to enhance the state’s supply of fresh water. With both undergraduate and graduate degrees in meteorology, he has worked for various Texas water agencies, administering the Texas Weather Modification Act. He was instrumental in organizing and supervising cloud-seeding research in Texas during the 1980s and 1990s, including the U. S. Bureau of Reclamation’s Southwest Cooperative Program in weather modification research and the National Oceanic & Atmospheric Administration (NOAA) Atmospheric Modification Program. Mr. Bomar helped construct a statewide rain-enhancement effort in Texas during the 1990s, which has grown from one cloud seeding project in 1994 to ten projects in 2003. The 2003 program, the largest known rain-enhancement effort in the U. S., covers over 51 million acres (or nearly one-third of the land area of the state of Texas). In administering State law governing weather modification operations, Mr. Bomar currently is responsible for licensing and permitting cloud seeding activities. He also oversees the administration of State grants for operational cloud seeding, whose cost in 2003 exceeded $4 million. He also heads up a new, federally funded research program in Texas to document convective cloud processes and test new seeding materials in 2004.

Dr. William R. Cotton Dr. Cotton is a Professor, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado. He joined the staff at CSU in December of 1974. At CSU he has received numerous awards including the Engineering Dean's Council award for excellence in atmospheric research, the College of Engineering Abell Faculty Research Graduate Program support Award, CSU Research Foundation Researcher of the Year Award and the Cermak Distinguished Graduate Advisor Award. He also served on several National Research Council Panels. In 1999 Dr. Cotton was the recipient of the Penn State University College of Earth and Mineral Sciences Charles L. Hosler Alumni Scholar Award. Dr. Cotton served as an editor for the *Journal of the Atmospheric Sciences* from 1993-1995, and as a co-chief editor from 1996-2000. He is a

Fellow of the American Meteorological Society and the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. He has published over 140 papers in peer-reviewed journals, eight chapters in books, authored one book, and co-authored two books. He has supervised over 35 Ph D. and 38 M.S. students.

His weather modification experience includes his doctoral dissertation research, as a team member on the NOAA Florida Area Cumulus Experiment, modeling studies of dynamic seeding and seeding of winter orographic clouds, and as the author of several review papers on weather modification, and co-author of several books reviewing planned and inadvertent weather modification concepts and status.

Mr. Byron L. Marler Mr. Marler has over 30 years of experience in applied meteorology. He is currently employed by Pacific Gas and Electric Company (PG&E) with headquarters in San Francisco and one of the largest service areas in the US. He supervises eight professionals, providing oversight and quality assurance on technical assignments ranging from weather modification operations, climate analyses, operational weather forecasting, air quality impact assessments, in-field measurements programs, and research projects. He is PG&E's expert on weather modification, having worked on the Lake Almanor and Mokelumme cloud seeding projects in the Sierra Nevada since 1975. He has led PG&E research projects in weather modification technology, including effectiveness evaluations, trace chemistry studies, ice-nuclei generator technology, cloud seeding model development, and snowfall measurement. He has performed design studies for cloud seeding programs for other utility companies and has had experience in the preparation of environmental impact assessment documents for operational cloud seeding programs.

Dr. Harold D. Orville (Chair) Dr. Orville is a Distinguished Professor Emeritus in the Department of Atmospheric Sciences at the South Dakota School of Mines and Technology. He served two terms as Interim Vice President of the University (1987, 1993) and as Head of the Department for 20 years. Dr. Orville joined the staff of the Institute of Atmospheric Sciences early in 1965. Since that time he has worked on cumulus dynamics and precipitation physics. In 1982, he served his sabbatical year as Leader of the Scientific Planning Group for the Precipitation Enhancement Project, a World Meteorological Organization sponsored activity. He served as a member of the Cloud Physics Committee, the Severe Local Storms Committee, and the Weather Modification Committee (Chairman, twice) of the American Meteorological Society, was elected a Councilor of the Society, and served on its Executive Committee. He was Chairman of the WMO Executive Council Panel of Experts/Committee on Atmospheric Sciences Working Group on the Physics and Chemistry of Clouds and Weather Modification Research from 1991 to 1999. He chaired the BASC committee in late 2000 that reviewed advancements in weather modification over the past 20 years.

Dr. Joseph A. Warburton Dr. Warburton is Executive Director Emeritus of Atmospheric Sciences at the Desert Research Institute, University of Nevada in Reno. His Ph.D is in Physics, the dissertation was "The Role of Particulates in Atmospheric Processes". He came to the US from Australia to develop the trace chemical techniques for measuring the very low concentrations of cloud-seeding chemicals in precipitation.

He has applied these specialized techniques in many of the weather modification projects in the US, Canada, Europe and Australia in studies of hail, rain and snowfall, and has published more than 20 papers on these subjects in the reviewed scientific literature. He has served on several Meteorological Society committees and chaired the Weather Modification Committee of AMS for 2 years. He served on the Editorial Board of the European *Journal of Atmospheric Research* for 10 years and has received all of the top honors and awards of the Weather Modification Association. He has specifically developed the majority of the trace physical and chemical procedures for analyzing atmospheric chemical substances in water at the parts per trillion levels of concentration, as well as isotopic methods for assessing in-cloud regimes where ice phase water capture occurs in the atmosphere. He has conducted large-scale cloud-seeding projects in Australia, Switzerland, Canada and the United States during his 30 years of research in the field of weather modification and provided professional assistance to Saudi Arabia, Iran, China, Taiwan and France in this field.

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