Some Reflections on Hailstorms and Hail Suppression

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INTRODUCTION

The Weather Modification Association (WMA) has this wonderful journal as a tool to promote the sharing of new and old ideas and insights between members. I would like to use it now to share some reflections on the subject of hailstorms and hail suppression. These reflections come from one who has been only peripherally involved in the study of hail development in hailstorms, and who has learned a little about transport and dispersion of seeding material in flanking cells, but one who has not been directly involved in hail suppression operations. I have had the opportunity to work for 15 years now with a wonderful observing platform that routinely penetrates hailstorms as a participant in collaborative convective storm field programs with various goals. These programs have included participants who have made fundamental contributions to the understanding of hailstorms and hail suppression. I have learned a great deal about hail from being around these folks at meetings, during field operations, sharing meals, and on long road trips. The following thoughts are offered in an effort to continue the discussions that seem to have waned since the demise of the National Oceanic and Atmospheric Administration (NOAA) Federal/State Cooperative Program in Atmospheric Modification Research.

THE CONCEPTUAL DIVIDE

In the 1993, the ***Journal of Weather Modification*** published back-to-back the then-current official policy statements on weather modification from the World Meteorological Association (WMO), the American Meteorological Society (AMS) and the WMA. (See ***J. Wea. Mod.***, vol 25, 1993, pp. 1-11). Many members of the WMA are members of the AMS, and as atmospheric physicists and meteorologists, WMA and AMS members are all connected to the WMO. Not all interested in weather modification research and operations had a voice in the preparation of these statements, or in their approval, but the statements can be taken as some kind of consensus among a nucleus of those actively involved in the respective organizations with an interest in activities related to weather modification or the knowledge base on which weather modification research and operations are built.

The WMO statement is the longest and most detailed. Concerning hail suppression by cloud seeding, it notes that promotion of beneficial competition, i.e., stimulation of the production of higher concentrations of hail embryos in the regions of the storm where updrafts and high cloud liquid water concentrations are conducive to the growth of hail, is the most common rationale for hail suppression by cloud seeding. Mention also is made of the concept of premature rainout. Cloud seeding operations in this context are thought to promote the earlier development and rainout of precipitation in flanking cells, reducing the transfer of small precipitation particles, either graupel or rain drops, to the main updraft and cloud-water-containing region where they might serve as embryos for the development of large hail. In this scenario, the earlier evolution of precipitation stimulated by seeding may lead to the earlier collapse of the flanking cells, and reduce the convective energy contributed to the main updraft area when the flanking cell merges into it, or itself becomes the main updraft. The use of numerical cloud models to provide new insights into hailstorm dynamic and microphysical processes is also mentioned. The WMO statement concerning hail suppression closes with the observation that some hail suppression projects are showing indications of success, but that much more research is needed in all phases of hail suppression.

The AMS statement on weather modification is much less sanguine concerning hail suppression. It opens its section on hail suppression with, "The efficacy of projects intended to mitigate the severity of hailstorms remains indeterminate." Further, it states. "Some [experimental and operational projects] suggest decreases in hailfall, but others have produced inconclusive results, and some suggest increases. Given the diversity of conceptual models, cloud selection criteria, seeding agents, delivery techniques, assessment methods, and the storms themselves, this is not unexpected." The use of cloud models to better understand cloud processes and test modification techniques is mentioned, with the caveat that outcomes of these modeling studies suggest both increases or decreases of hailfall, depending in the circumstances. This section of the AMS statement also closes with the usual (for a scientific group, anyway) aphorism that more research is needed.

The AMS statement was drafted by experts in atmospheric physics and severe storm phenomena. This group probably included some of the same experts who helped draft the WMO statement. The AMS statement has a harsher edge to it from the point of view of those who are attempting to practice hail suppression. While the WMO statement describes the various rationales for hail suppression (beneficial competition, premature rainout, etc.) the AMS statement emphasizes the extreme simplicity of the conceptual models on which these rationales are based (without discussing them in detail), compared to the extreme complexity of most hailstorms.

An updated AMS statement on weather modification was adopted by the AMS Council in 1998. It is split into two sections, one a relatively concise statement on various aspects of weather modification, and the other a scientific background. Both can be found in the ***Bull.***

Amer. Meteor. Soc., vol. 79, no. 12, 1998, pp. 2771-2778, and reprinted in *J. Wea. Mod.*, vol. 31, 1999, p. 143-150. The section on hail suppression makes a stronger acknowledgement than in the earlier AMS statement that statistical assessments of operational projects were showing reductions in crop hail damage, but again contained the affirmation that the physical linkages between cloud seeding and reduced crop damage are not established. The scientific background discussion emphasizes the uncertainties and diverse outcomes in both the statistical evaluations and physical understanding, is little changed from the discussion in the earlier statement, and is less positive than the concise policy statement that accompanies it.

The WMA statement is the shortest of the three statements on weather modification. It is also the earliest of the three, drafted in 1984. With respect to hail suppression, it notes, "Little has yet been shown through careful study of the physical behavior of the interior of storms from suppression efforts. Therefore the scientific linkages establishing hail suppression are not well established, although the assessment of surface hail differences are generally suggestive of successful suppression in the realm of 20-50% reduction." The WMA statement, befitting the operational perspective of the majority of its members, stresses the fact that assessments show the operations to generally reduce hailfall or hail damage, despite the fact that the physical details connecting cloud seeding with reduced damages are not well understood.

The difference in perspectives of scientists seeking to understand severe storm processes, and weather modification practitioners seeking to achieve a particular result, was nicely summarized in Howell (1986). He pointed out the contrast between the then-current AMS statements on weather modification, on weather forecasting, and on damage from extreme weather phenomena. In the statement on weather modification lack of scientific understanding was emphasized as casting doubt on the efficacy of weather modification operations, as it was in the two more recent statements discussed above. But in the statements on forecasting and weather-related damage, there was no corresponding assertion that incomplete understanding of atmospheric dynamics and physics is a basis for denying the efficacy of then-current procedures for forecasting weather on various time and space scales, or predicting damage resulting from extreme weather phenomena such as high winds. Many practitioners of weather modification, and researchers applying their knowledge of atmospheric dynamics and physics to refining weather modification practices, accept studies showing positive effects from some approaches to weather modification. They look at their work as making use of what is known for the public good, and as continuing to refine knowledge to improve what is already a successful practice. On the other hand, many researchers interested in understanding convective storm phenomena are overwhelmed by the extreme variability and unpredictability of convective storms and do not put credence in statistical results for which they do not have sufficient physical understanding.

Among non-specialists, there can be an emphasis on the negative side of the uncertainty, such as possible increases in hailfall and decreases in rainfall within or downwind of operational areas, leading to vigorous political opposition in some regions, most recently in northwest Kansas, for instance. Such opposition by non-specialists can often enlist the willing support of those with scientific credentials who emphasize the need for physical understanding prior to putting procedures into practice.

CONCEPTUAL MODELS and THEIR VALIDITY

In addition to the conceptual models invoking beneficial competition and premature rainout that were mentioned above, a WMO meeting of experts to review the present status of hail suppression convened in 1995 lists several additional conceptual models. (WMO, 1996). This list, originally based on discussions related to the North Dakota Cloud Modification Program, contains, in addition to beneficial competition and early rainout, the concepts of trajectory lowering, hail suppression through glaciation of supercooled cloud water in the main hail growth region, the specific mechanism of promotion of coalescence as a mechanism for promoting early rainout or beneficial competition (earlier discussions of early rainout and beneficial competition were focused mainly on effects of glaciogenic seeding on these processes), and dynamic seeding to redistribute the convective available potential energy in the environment over a larger number of storms, resulting in more but less vigorous storms.

There is a willingness of part of the operational weather modification community to accept simplified conceptual models of storm processes as a basis for weather modification practices. There is the implicit hope within this contingent that further research, and careful observations connected with operations, will lead to improved understanding of storm processes and refinement of these conceptual models. Further, the clients funding operations often can barely grasp the simplified conceptual models, much less grasp the significance of recent results from sophisticated field studies and modeling efforts. The operational community does not need more sophisticated models in order to satisfy most of its customers.

Given the recent lack of public or private funding for rigorous research focused on weather modification, recent efforts to improve understanding predominantly have come from observations connected with operational programs and analysis by the operators themselves. As there is little expectation in the near future for large publicly-funded scientifically-designed weather modification projects such as the National Hail Research Experiment (NHRE) and Grossversuch projects of the 1970's and 1980's, it is likely in the near future that further refinement will continue to come from careful observations connected with operational programs, and that the operators themselves will be responsible in a major way for improving physical knowledge of storm processes and their modification.

Tests of Conceptual Models using Observations *from Operational Programs*

It is usually not possible to introduce randomization into hail suppression operations. Therefore purely scientific randomized studies like NHRE and Grossversuch cannot be grafted onto operational programs. However, it is possible to perform post hoc analyses of operational results and establish whether or not there is a trend toward more effective hail suppression when, for instance, operations were conducted in a more effective manner according to conceptual models of hail suppression on which the operations are based.

Examples of recent studies of this sort can be found in reports presented at recent conferences on weather modification. Dessens et al (1998) for instance estimated the relative amounts of seeding material ingested by storms passing over their network of ground generators for dispersing silver iodide smoke. They found that the number of hailstones larger than 0.7 cm diameter resulting from these storms decreased as the estimated mass of ingested seeded material increased. Abshaev (1999) and Kraus (1999) compare the radar-defined evolution of storms that were seeded at a certain stage in their evolution with evolution of unseeded storms starting from a similar stage in their evolution. These studies involve storms in several different parts of the world. They also are based on operational programs with dramatically different seeding strategies. The Russian-directed programs discussed by Abshaev use rockets to deliver seeding material directly into regions where hail is expected to develop, while the program from which Kraus derives his insights involves airborne seeding using droppable and burn-in-place pyrotechnics and solution burners, focusing on flanking cells rather than main updraft areas. The dispersed nuclei in the different sets of operations also have different properties. Despite these differences, Abshaev and Kraus both find evidence for reduced hailfall, and changes in radar evolution consistent with premature rainout and/or trajectory lowering in seeded storms compared to unseeded ones. As radars respond more directly to particle size than particle number, it is difficult in radar-based studies to find direct evidence for beneficial competition, although the observations do not preclude enhanced beneficial competition as the result of seeding.

There have been many more such studies associated with operational hail suppression programs in the Balkan states, China, and elsewhere. Some are based on radar observations, others on observations of hail at the ground. The results are taken by most scientists as suggestive, but not conclusive. It is very difficult in such studies to be certain of an unbiased sample of treated and untreated storms, or more effectively treated and less effectively treated storms, upon which to base a study. It also is difficult for an organization whose prime objective is operations to be able to devote the time and effort to careful study that is required of a truly scientific effort. It is an unfortunate characteristic of weather modification that operations are typically less expensive than scientific evaluations. Public agencies, insurers, etc., who fund operations are often willing to accept uncertainty in the outcome of operations they fund, rather than significantly increase costs to reduce the uncertainty concerning the physical basis for the outcomes or the sign or magnitude of the outcomes themselves. Therefore contracts for hail suppression operations usually do not contain large amounts of funding for evaluation.

Nevertheless, studies connected with operational programs continue to contribute to understanding of how hail develops in storms and refinements in conceptual models for hail suppression by cloud seeding. The continuing increase in computing power available at the modest levels of funding associated with operational programs will facilitate more extensive and more sophisticated post hoc radar analyses like those of Abshaev (1999) and Kraus (1999). However it is unlikely that scientifically acceptable detailed physical justification for hail suppression conceptual models will be possible without incorporating in situ measurements and detailed numerical modeling of cloud processes. Although modeling efforts benefit from the same increases in affordable computing capability that facilitate radar studies, and operators can today contemplate running relatively sophisticated cloud models on desktop computers as part of their everyday operations, in situ observations are inherently more difficult and expensive to incorporate into operational programs, particularly in situ observations in regions where hail embryos and hail itself are developing. It will be a challenge for operators to try to obtain more often, and in more regions, useful in situ measurements such as aircraft rate-of-climb, cloud water, ice particle concentrations, and other rudimentary physical observations. Some aircraft used in dispersing glaciogenic agents in the upper regions of flanking cells currently obtain such observations during operations, but the data are rarely analyzed and presented at open meetings or in research publications.

Other insights concerning the conceptual models used as the basis for hail suppression come from scientific studies of other aspects of severe storms, but bearing on hail development and ultimately on hail suppression. I would like to turn now to some recent observations from such studies and discuss how they relate to the conceptual models discussed above.

Tests of Conceptual Models using Observations from Scientific Convective Storm Studies, and Useful New or Additional Observations from Operational Programs Suggested by Scientific Studies

While there have been no recent purely scientific studies focused specifically on hail suppression in the U.S., there have been several recent field studies focused on convective storm initiation, tornadogenesis, the link between the specifics of storm electrification and development of hail, and the use of polarimetric radars to map microphysical characteristics of whole convective storms. In addition, during a period extending from the early 1980's through the early 1990's there were scientific studies piggybacked on hail suppression operations in North Dakota supported in part by the NOAA Federal/State Cooperative Program in Atmospheric Modification Research. The armored T-28 operated by the South Dakota School of Mines and Technology (SDSMT), with which I work, has been involved in several of these. Here is my view of how in situ observations from the T-28 and other facilities involved in these field programs illuminate conceptual models of hail development and hail suppression, and how operational programs can archive new or additional data to test the conceptual models on which their operations are based.

One insight important to me was gained by being part of the piggyback research operation in North Dakota during 3 field seasons. During this study there was an effort to disperse an inert gaseous tracer at cloud base, along with radar chaff, and follow the transport and dispersion of these materials through flanking cells or isolated cumulus congestus using aircraft with gas analyzers and also radar to follow the chaff. The goal was to evaluate how effectively, if dispersed in a similar fashion, glaciogenic seeding material would be transported to the –5 to –15 C region within such clouds where it might modify the local cloud microphysical characteristics. The selection of candidate clouds for these tracer tests was somewhat analogous to, but not exactly the same as, the selection of candidates for operational seeding for hail suppression or rain enhancement. At the WMA meeting in Park City in 1998 I presented a discussion concerning the relatively large number of times during these studies that most of the dispersed material underwent little transport, and the one case (Bloomer and Detwiler, 1996) in which it underwent too rapid transport (leading to insufficient dispersion by the time the material reached the zone where its activity would lead to microphysical changes in the cloud). The conclusion I drew was that proper treatment using aircraft dispersal of seeding agents is difficult and that probably many seeding operations did not result in transport and dispersion of material to critical regions as specified in conceptual models. Given the overall project evaluations showing reduced hail sizes or hail damage due to seeding, it was speculated that these seasonal reductions resulted from a few cases per season where everything "worked" according to plan.

These observations certainly are not unique. There are other examples of studies by my own predecessors at SDSMT in which it was observed that a significant fraction of operational airborne seeding operations in the U.S. High Plains region were not timely or effective, including Smith et al (1985) and Boyd (1974). There no doubt are many other such sets of statistics connected with other operational programs. This is one area in which operators typically have good documentation, and more complete study and open discussion of the effectiveness and timeliness of delivery of seeding material during operations according to the conceptual model appropriate to the operation will improve understanding of the problems and lead to development of more effective operational programs.

Related to the issue of effective targeting and delivery is the character of the seasonal spectrum of storm sizes and damage from storms. There generally is an exponentially decreasing number of storms as the damage level associated with the storms increases. In most areas of the world, most of a season's hail damage will come from one or two particularly damaging storms. The experience during our piggyback field programs in North Dakota was consistent with this distribution. Are larger more damaging storms generally more easily targeted and treated? It certainly was not true in our piggyback operations. Probably this is not true in general. In fact, in many programs there are suspension criteria that lead to the largest storms not being treated at all. This follows from speculation that it may be technically impossible to effectively treat large storms using current seeding technology with a predictable result (e.g. Atlas, 1977), and also from the legal desire for operations to be disassociated from the almost certain costly damage associated with large storms. If the largest storms cannot be treated effectively, either for physical or liability reasons, then what is the physical basis of statistical studies showing reduced seasonal hail damage in areas protected by hail suppression operations? Again, statistics on storm intensity, hailfall, and operational success in timely treatment, from operational programs, can be used to provide new insight into this issue.

One of the fundamental assumptions in glaciogenic seeding is that the natural atmosphere is usually deficient in ice nucleating aerosol particles, and that introduction of artificial ice nuclei will lead to increased ice particle concentrations in critical regions of storms, leading to beneficial competition, premature rainout, trajectory lowering, etc. To the best of my knowledge, no current operational program monitors ice nuclei concentration in the ambient air. It was done for only one year during our piggyback studies, and then only with a limited number of surface and airborne in situ samples. (Demott et al, 1996). Airborne observations associated with these ice nuclei samples showed that, typically, ice particle concentrations were higher than the concentration of ice nuclei effective at corresponding in situ conditions as estimated from surface samples and also bag samples of aerosol near and within clouds. Is there any serious reason to question the assumption of deficiency of natural ice nuclei and its relationship to ice particle concentration?

Schaefer (1978) suggests that over the period from the late 1940's to the late 1970's, his subjective personal observations indicate a higher prevalence of visibly glaciated clouds at moderately supercooled conditions. T. J. Henderson (personal communication) recently made the same assertion based on in-cloud observations made during decades of seeding operations. Are these observations biased or perhaps too qualitative to be taken seriously? Yang et al (1999) report on limited observations of concentrations of ice nuclei made in Beijing in 1963 and 1995, using the same technique in both years. They report that the concentration of aerosol particles active as ice nuclei at –20 C, near the ground at their institute, increased by a factor of 16 over the 22 years between the two observing periods.

These observations of glaciated clouds and ice nucleus concentrations are limited, and in the case of Schaefer's and Henderson's visual observations, subjective, but certainly not consistent with the usual assumptions in most conceptual models. In the context of operational programs, consistent monitoring of ice nucleus concentrations can be used to address the natural variability of ice nucleus concentrations and the hypothesis that hail can be suppressed by artificially increasing ice nucleus concentrations. Although the more sophisticated and expensive ice nucleus monitoring techniques probably work best, even relatively simple techniques (e.g., Schaefer and Day, 1981), if followed consistently from season to season, can provide a baseline for evaluating the variability of ambient concentrations and the assumption of always-deficient ice nucleus concentrations.

Despite our best attempts, during the T-28 operations referred to above, and during extensive earlier operations in projects such as NHRE (1972-1975), the Cooperative Convective Precipitation Experiment (CCOPE, in 1981), Grossversuch (1982 and 1983) and others, relatively few in situ observations have been obtained of ice particle concentrations in storm zones where hail is growing, and even fewer in seeded storms. An example of observations from one such storm penetration is shown in Figure 1.

These observations in this storm suggest natural ice particle concentrations at the –13 C level exceeding 10 l^{-1}, a typical target concentration which cloud seeders try to achieve through cloud seeding. But this is only one observation at one point in the evolution of a storm that was pro ducing ¾-inch diameter hail at the ground at the time. Zones of hail growth often persist for only short periods, represent only a tiny fraction of total storm volume, and probably vary significantly in their properties both through their own history and by comparison to other zones in the same or nearby storms. Among currently available aircraft, only the armored T-28 can routinely and safely sample in these zones, so even with suitable instrumentation, there is little hope of obtaining additional in situ observations from operational seeding aircraft used in hail suppression cloud seeding operations.

Even with such in situ observations, it takes careful analysis of both airborne and supporting radar and surface observations to develop an understanding of hail growth processes. Heymsfield and Hjelmfelt (1984) used T-28 observations from an entire field season, along with microphysical modeling, to show that ice multiplication should be common in many hailstorms in Oklahoma. Rasmussen and Heymsfield (1987) used T-28 observations and modeling from one storm in southeastern Montana to show that shedding of supercooled water drops from hail in wet growth can be an important source of embryos in vigorous High Plains hail storms. Both ice multiplication and shedding can result in hail stone concentrations that are independent of ambient ice nucleus concentrations, at least in clouds meeting certain criteria. During NHRE, there also was no observed correlation between ambient ice nucleus concentrations and hail characteristics from unseeded storms.

There thus is no firm evidence based on in situ and surface observations of ice nuclei and ice particles that additional embryos result from seeding, that they can be transported to hail growth regions, caused to grow within these regions, or even that additional embryos will lead to more and smaller hailstones. Radars, even polarimetric ones, are not effective for monitoring embryo concentrations, although they may show patterns of storm evolution consistent with one or more conceptual models for hail suppression based on increased embryo concentrations due to seeding. The deeper aspects of such questions probably are better resolved using appropriate numerical modeling. Operational programs may be able to provide ice nucleus concentrations and radar evidence to address these issues, but numerical modeling is probably not likely to become one of their operational tools at least in the near term.

One final area that is important to mention is the wide variety of growth trajectories inferred to produce large hail in typical hailstorms. These trajectory studies are associated with scientific research projects. They can be done using multiple-Doppler wind syntheses from convective storms, or wind fields calculated from numerical cloud simulations. Two approaches generally are used. One is calculating forward in time the growth of ice particles started as small hail embryos at various locations within the storm, making certain assumptions about the microphysical environment in various storm regions through which the growing particles move based on radar reflectivity and computed updraft, or using directly computed environmental parameters from the cloud model. The other approach is to identify regions of hail in-cloud, or where hail reached the ground, based on direct observation or radar signatures, then integrate

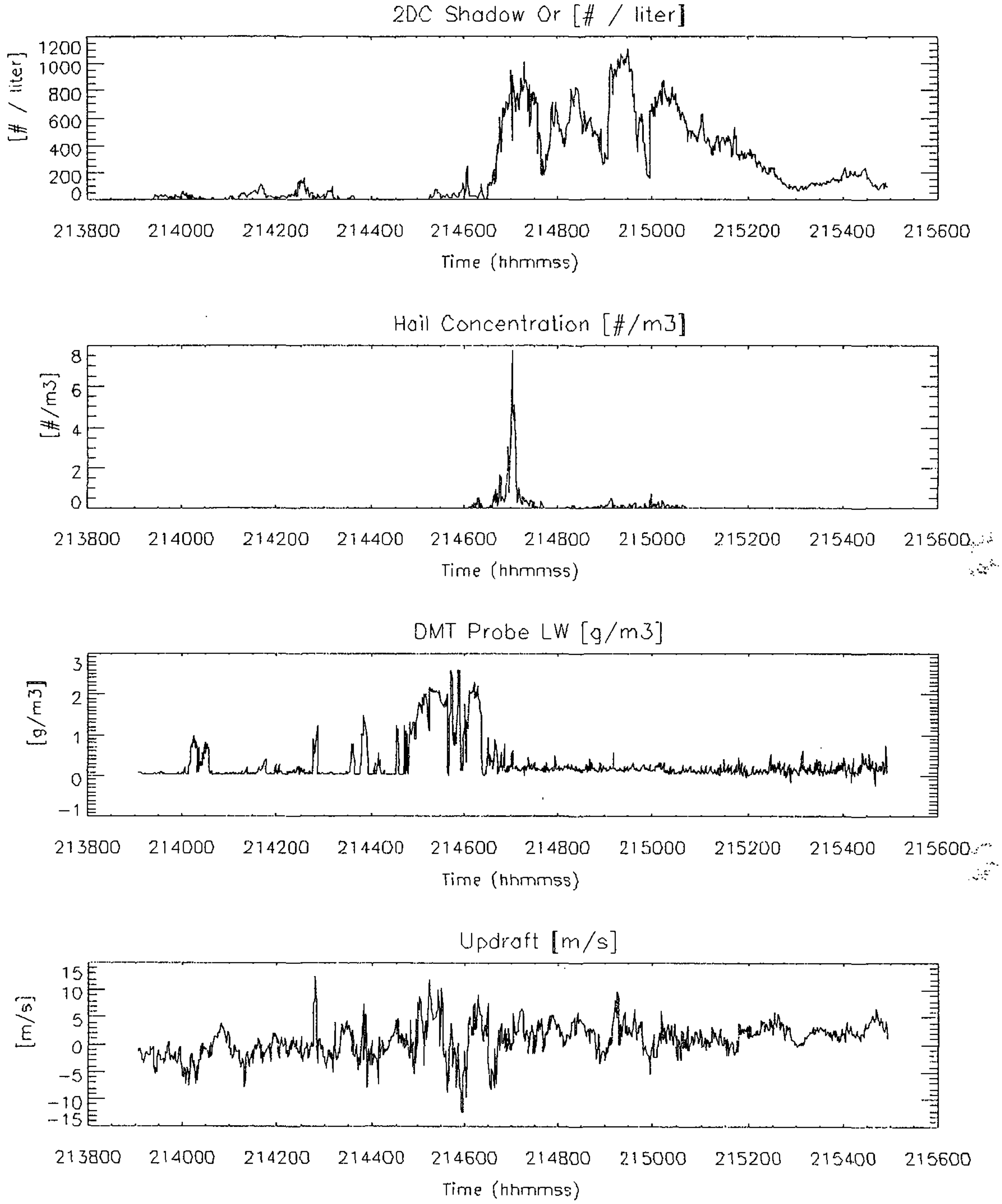

Figure 1 – Ice particle concentration, hail (particles with diameter greater than 5 mm) concentration, cloud water concentration, and vertical wind are shown during a pass from front-to-rear through an asymmetric mesoscale convective system at an altitude of 6 km MSL (-13 C) over northeastern Colorado on 11 June 2000. Small cells with weak updrafts and low ice particle concentrations were encountered until just after 21:44:00. The main updraft regions contained updrafts and downdrafts reaching 10 m s^{-1} in magnitude. The updrafts contained cloud water concentrations exceeding 2 g m^{-3} and low ice particle concentrations. Hail is found growing in the transition zone between the second updraft region and its neighboring downdraft. The remainder of the pass is through the trailing stratiform region with negligible vertical motions and cloud water.

backward in time through the inferred or calculated storm environment to find the embryo source regions.

Growth trajectories based on multiple-Doppler radar syntheses from High Plains convective storms were performed by Heymsfield et al (1980), Dye et al (1983), Miller et al (1983), and Heymsfield (1983) using NHRE case studies. Knight and Knupp (1986), and Miller et al (1988 and 1990) did similar studies on CCOPE storms. In these studies the wind fields are deduced with fairly coarse resolution, no better than 1 km and often coarser. Further, the wind and microphysical fields typically are assumed steady for periods of 5 to 15 min or more. With these limitations, the following general conclusions were reached concerning hail growth trajectories.

In most cases, hail growth to diameters greater than 1 cm did not result unless embryos first developed to millimeter diameters in flanking or feeder cells with modest updrafts. This result fits most of the conceptual models used in airborne cloud seeding in the U.S. and Canada, and in many other parts of the world as well.

There were multiple possible paths for transport of embryos into the fringes of the main updraft followed by growth to hail sizes. One class of paths involved transport upward into the upshear overhang region from which the particles descended into the mid-altitude upshear updraft flank region. Another class of paths involved transport at roughly constant altitude from the upper regions of smaller flanking cells into the middle altitude regions around the updraft. A third class of paths involved embryos precipitating downward out of flanking cells, or the upshear overhang of the main cell, possibly low enough to produce melting, and subsequent ingestion back in to the base of the main updraft followed by growth to hail sizes. Growth from embryo size to hail size in the core updraft itself typically did not occur, due to the growing particle being lofted too quickly above the regions containing significant supercooled water concentrations.

In larger more persistent and more steady state storms, recirculation of embryo particles from the upshear overhanging anvil region downward and back in to the low level inflow was a more likely trajectory than in the weaker, more multicellular, more rapidly evolving storms. In most cases, the trajectories along which hail grew were simple once up and then down, and nearly straight-line in horizontal projection. Complicated looping trajectories were not common. In multicellular storms, hail-producing trajectories depended on a fortuitous and transitory arrangement of flanking cells and main updraft cores.

Trajectory modeling studies by Farley and Orville (1999) using numerical models indicate that the source region for embryos which grow to large hail can be of quite limited lateral extent, on the order of 100's of meters. Field studies of hailstorms using a vertically-pointing Doppler radar are quite consistent with these numerical modeling results. (Thomson and List, 1999).

These studies addressed only the trajectories and growth of particles, not the concentrations of embryos or hail that might be found at various stages along the growth trajectories. Results of these studies cannot be used at all to address the concept of beneficial competition. Although the original studies showed little impact of starting embryo size, with further elaboration and a focus on the effect of embryo size, new trajectory calculations could be used to evaluate the validity of the concept of early rainout or trajectory lowering.

Many of the participants in these studies have been colleagues of mine on field projects, in seminars, and elsewhere. We have discussed hail suppression issues occasionally. Few of them consider it likely that cloud seeding with glaciogenic agents will have a predictable effect on hail development. Although the concept of hail development starting with growth to embryo sizes in flanking cells followed by transport to the main updraft region is supported by these studies, the relationship between embryo concentrations and subsequent hail production is much more complex than envisioned in the simple conceptual models invoked by practitioners of hail suppression. The common observation of the finite length and often irregular patterns of hail swaths and hail streaks is testimony to the transitory storm structures that produce hail, and the difficulty of introducing seeding material at a place and time where its effects can be predicted.

Nevertheless, studies showing hail damage reduction on the average in regions where appropriate cloud seeding operations are conducted suggest that there is an effect of seeding that stands out in the aggregate. Given the lack of public funding for research, my own opinion is that operational projects, with their dedicated radars and trained airborne and surface-based observers, are in a position to monitor storm structures and verify to some extent the applicability of their conceptual models. Dual or multiple Doppler wind field synthesis and trajectory calculations probably are not feasible for any operational projects, currently. Techniques involving single Doppler and fine scale reflectivity analyses (Brown and Meitin, 1994) can increasingly be automated and should prove useful in the near term for this type of structure evolution analysis. To address issues raised by the skeptics, these studies will probably have to be more sophisticated than those of Abshaev (!999) and Kraus (1999).

SUMMARY AND CONCLUSIONS

Some are able to accept reports of hail suppression due to cloud seeding based on statistical studies of results from operational programs. Others, citing the lack of a clear physical explanation for these results, and inconclusive scientifically-designed trials of related seeding concepts, will not accept these results. The current politics of scientific funding suggest that a significant infusion of new funds for purely scientific trials of various hail suppression mechanisms is unlikely. Thus, there is little hope for changing the current contradictory views toward hail suppression among those knowledgeable concerning the relevant meteorology and physics.

Progress in resolving this conflict will in the near term be the responsibility of organizations conducting operational projects, hopefully with additional if limited analytical help from colleagues in academia and government. A simple comparison of hail damage in seeded areas to that in unseeded areas is not sufficient. Additional effort is required.

Observations collected during operations involving airborne seeding should be augmented where possible to include more extensive airborne observations of ice particles and water drops. The role of aircraft should be expanded from purely dispersion of agents and visual observations to monitoring key parameters associated with different steps in the seeding conceptual model. Does seeding indeed increase embryo concentrations in flanking cells? Does it lead to earlier rainout from bases of flanking cells?

Some observations of ice nuclei concentrations at the surface should be conducted as a standard part of all operational projects.

Radar observations collected during operations should be analyzed to extract information with which to evaluate the conceptual models upon which the operations are based.

Objective or quasi-objective criteria should be developed so that each operational seeding event can be classified according to its timeliness and the expected result based on the applicable conceptual model. If statistics based on these operational evaluations were compiled and presented for discussion, to the extent allowed by the proprietary nature of some of the observations, operators could gain scientific and political support and insight from their more academic and research-oriented colleagues.

Some years ago Stan Changnon presented a talk in Rapid City in which he compared the need for more knowledge concerning cloud seeding and its impacts with the situation in nuclear physics circa 1942. He then compared the relative amounts of funds available to the weather modification community and the Manhattan Project. We all know that the funds available for development of hail suppression techniques have been miniscule in comparison to such massive efforts as the Manhattan project. Within its funding limits, hail suppression research had its window of opportunity, its moment in the national spotlight, in the 1960's and 1970's. The problem of achieving enough theoretical and practical knowledge to enable predictable hail suppression operations proved too difficult to solve before the window closed. To many today, predictable hail suppression seems implausible. The problem is still intriguing both to workers in the field and to many elements of the general public. With effective use of limited resources, perhaps we can strive to make progress and make it possible to reopen the window at least a crack.

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