Some New Approaches in Hail Suppression Experiments[1]

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ABSTRACT

It is suggested that progress in hail suppression research requires simultaneous improvements in methods of evaluating seeding effects and in monitoring the physical structure of the hailstorm and the hail growth processes. On this basis a case is made for the extensive use of multiple Doppler radar and chemical tracer techniques.

1. Introduction

Hypotheses exist which suggest the possibility that hail may be suppressed by seeding convective clouds with ice nucleating agents such as silver iodide. The economic benefits of even partially successful hail suppression would be substantial since in the United States alone the annual damage to crops amounts to more than $600 million (Borland, 1975). Claims of decreases in hail damage due to seeding have been made but there is no general agreement among the scientific community about their validity (Hitschfeld, 1974). The National Hail Research Experiment (NHRE) is perhaps the most ambitious of a number of programs set up to evaluate the efficacy of seeding, but the hail problem is a complex one and this experiment has yet to provide statistically significant evidence one way or the other. However, five years after the inception of NHRE, we now have a clearer appreciation of the problems involved, and the purpose of this paper is to identify some of the weaker links in experiments of this kind and to suggest some possible remedies. Two aspects of hail suppression experiments will be considered: 1) evaluation of seeding effects, and 2) monitoring of the physical structure of the hailstorm and the hail growth processes (with and without seeding). The approaches discussed in this paper are intended to address both issues at one and the same time. Indeed the issues are inseparable: in the absence of very well-defined seeding effects no credible evaluation is likely to be achieved without physical understanding; neither could any seeding method evolved for one area confidently be transferred to another area without some understanding of hail processes and storm types.

The remedies we shall be proposing are radical and expensive to implement. In order to see why we feel compelled to look for such approaches in hail suppression research, consider the following (partial) list of difficulties:

1) There is a high degree of variability in space and time in the output of hail from a storm. Not only does this create difficulties in achieving an adequate density of surface hail measurements to define the storm output but it also obliges the experimenter to observe large numbers of seeded and unseeded units in order that any differences in the averages between the two may be detected with adequate confidence. Unfortunately, however, the frequency of occurrence of hailstorms within most areas large enough to be instrumented adequately is quite small, e.g., about 20 hail days per year in the 1600 km² NHRE Target Area, of which just 4 days contribute about 80% of the overall damage (Atlas, 1977a). Unless covariates can be found to counter the effects of natural variability and the physical effects of seeding can be monitored, this means that hail suppression experiments may have to go on for unacceptably large numbers of years to reach a significant result.

2) The efficacy of seeding depends on the concentration of seeding material reaching certain parts of the storm. However, the "seededness" of the storm is a difficult quantity to measure. It is not enough to monitor the seeding rate and location with respect to the storm; we also need to know, among other things,

(i) the trajectories of the seeding material in the storm, the trajectories of particles destined to become

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hailstones, and whether and where these two sets of trajectories intersect, and

(ii) the rate of diffusion of the seeding material in the cloud, and whether the concentration of still-active seeding material which reaches the region of hail formation exceeds the concentration of freezing nuclei that occurs naturally.

(3) It is possible that the effect of seeding differs from one type of storm to another (Browning, 1975) and with the microphysical and dynamical conditions even within the same type (Danielsen, 1975). Thus opposite effects might be produced by seeding in a similar way when the physical characteristics of the storms differ. Unless the physical characteristics of the storms are monitored to permit the seeding effects to be stratified accordingly, there will be the danger of lumping together real effects of opposite sign and therefore reaching an inconclusive statistical result. Problems of this sort have been elaborated on by Atlas (1977b).

2. Two new approaches

We now discuss the possible roles of multiple Doppler radars and chemical tracers in a hail suppression experiment, since we believe their use might go a long way toward solving some of the problems mentioned above. We note at the outset that, although these techniques in themselves are not new, some aspects of their use as presented here are conceptual and speculative so that detailed feasibility studies would be required before they could be exploited with confidence. However, because of the critical nature of the problems they are intended to address and the failure of more conventional methods, we believe it worthwhile to consider these new approaches seriously.

a. The use of multiple Doppler radars

The effective natural variance of a highly variable phenomenon such as hail can be reduced through the use of covariates or predictor variables which account for a significant part of that variance. That is to say, the number of hailstorms that need to be sampled can be reduced by finding a measurable or predictable parameter (covariate) which is so well correlated with the occurrence of hail (the target variable) under natural conditions that one can assess the hail size in seeded storms that would have occurred in the absence of seeding. In this way any difference in the target variable in treated and untreated experimental units may be more confidently regarded as a measure of the treatment effect. Now the size of hail depends on both the storm kinematics and the microphysics. Seeding affects both, but probably the latter more. Thus an attractive possibility would be to develop a measure of the hail potential that is determined by the airflow, in particular by the characteristics of the updraft. We shall call this the Dynamic Hail Potential (DHP). When evaluating the efficacy of seeding we would like to be able to determine the DHP for each storm in the target area and regress the hail size against DHP separately for seeded and unseeded storms.

The utility of the DHP as a covariate depends on the updraft being relatively unaffected by the seeding, at least in the short term. There are two ways in which seeding might affect the updraft. One is associated with increased buoyancy due to earlier glaciation; the other is associated with changes in water loading due to possible changes in size, and hence location, of the precipitation particles. The object of current seeding practice is to increase the number of competing hail embryos rather than to cause extensive glaciation to occur much earlier than otherwise; however, even if glaciation were significantly hastened, it still would cause only a small fractional increase in buoyancy since the updrafts in most hailstorms are characterized by a large temperature excess to begin with. On the other hand, if the seeding were to achieve its intended effect and lead to more small hailstones and fewer large ones, the location of these stones within the updraft would change as a result of their different fallspeed and any dynamical effects due to loading of the updraft would be redistributed. However, the feedback effects on the dynamics would not begin to occur until some time after the seeding, in which case it would still be useful to determine the DHP early during the seeding period as the predictor variable. Of course it is also of interest to continue measuring the DHP in order to assess whether any dynamical changes apparently produced by seeding are in the desired sense.

One way of determining the DHP is by means of numerical models using data from proximity soundings. Many of the models predict the maximum updraft velocity w_m and the temperature $T(w_m)$ at which it occurs, and these are then entered into a nomogram to predict the maximum hail size. A number of studies have shown quite good correlations between predicted and observed hail size (e.g., Dennis and Musil, 1973; English and Wong, 1976) but in some areas such as northeastern Colorado, where mesoscale convergence fields are thought to have a particularly large influence on hailstorm genesis, predictions based on statistical regressions using proximity soundings are poor (Modahl, 1975). These poor predictions result partly from the difficulty in obtaining a representative sounding and to some extent they are due to the size, vigor and degree of mixing of the updrafts varying from one cell to another in an unpredictable manner depending on the detailed pattern of convergence near the surface. In any event, the great variability in maximum hail size from one cell to the next in space and time bears testimony to a degree of variability from one cell to the next that surely must be difficult to predict by numerical models based on a proximity sounding. For this reason we believe it will be more profitable to determine the DHP for specific updraft cells using actual observations of the hailstorm updrafts rather than by using model calculations. Although it is desirable to determine the entire three-dimensional field of motion, the kind of parameters most likely to be important in determining the DHP are w_m and $T(w_m)$.

The state of the art is such that we now have the opportunity to observe the updraft structure for all storms within a reasonable target area by a combination of the following techniques:

1) The main tool would be multiple Doppler radars operating in pairs or, as discussed later, perhaps in threes (Lhermitte and Miller, 1970; Lhermitte, 1968). One of the limitations here is the restricted area of coverage of any one pair. However, with n radars, we have $\sum_1^n (n-1)$ pairs such that 4, 5 or 6, radars would give 6, 10 and 15 pairs, respectively. Four or five Doppler radars would be sufficient to cover an area somewhat larger than the 1600 km² now in use by the NHRE. Since the measurement of vertical drafts involves the integration of the divergence equation from the surface upward and since no detectable echoes may be present in the lower portions of some updrafts, the radar data would need to be supplemented by 2) and 3) below.

2) Measurements of updraft velocity near cloud base should be made by an aircraft flying at that level. This aircraft might also release tracer and seeding materials. It should also be releasing chaff packets and be measuring the natural nuclei ingested by the storm.

3) Provided the Doppler radars were scanned with a rapid cycling time it would be possible to keep track of individual chaff packets and hence determine the air motion from their displacement within the weak-echo regions. If released directly below the updraft core, their dispersion would probably not be such as to make them untrackable or to interfere unduly with the interpretation of the three-dimensional precipitation pattern.

The other way of using the Doppler radars would be to use them to scan each storm three at a time rather than in pairs. Although this approach reduces the total number of storms that may be scanned simultaneously by a given array of Doppler radars, it has the major advantage of providing the vertical air motion directly at each point without invoking the continuity equation and therefore relaxing the requirement for 2) and 3) above. At the same time the three-Doppler approach provides a crude measure of the spectrum of particle fallspeed and hence an indication of maximum hail size and its distribution within the cloud. This knowledge would be valuable in the evaluation of seeding effects, especially in view of the difficulty in obtaining a sufficient density of surface observations to define the hail output. The same knowledge would also be valuable, when considered together with the Doppler airflow measurements, for determining hail trajectories within the cloud.

As a guide to what might be achieved by using a Doppler-derived estimate of DHP as a covariate of maximum hail size, we refer again to the model results of Dennis and Musil (1973) and English and Wong (1976). They reported correlation coefficients between predicted and observed maximum hail sizes of $r=0.76$ and $r=0.85$, respectively. A correlation coefficient r implies that the covariate accounts for r^2 of the total variance. Thus a correlation coefficient of 0.8 would imply a 64% reduction in variance. The basic test of the significance of the difference of the means of the test variable for treated and untreated units is the magnitude of the ratio $(\bar{x}_t-\bar{x}_u)/(\sigma^2/n)$, where $\bar{x}_t$ and $\bar{x}_u$ are the average test variables in treated and untreated units, respectively, (σ^2/n) is the effective variance of the mean of x, and n is the number of samples. We therefore see that a reduction of 64% in σ^2 permits a corresponding reduction in the number of samples required and thus a substantial reduction in the duration of the experiment. However, the good correlations mentioned above for model predictions using proximity soundings refer to the largest hail produced by a group of storm cells. As already mentioned, the numerical model predictions do not account adequately for the variations from cell to cell and from time to time that may be produced by undetected variations in the mesoscale field of convergence. The Doppler approach, on the other hand, can measure the evolving dynamical structure of the individual cells. Thus we believe that, in the case of a seeding experiment in which it is important to assess the DHP separately for each cell, the Doppler radar approach offers the best promise for decreasing the variance while at the same time producing the other detailed information about the storm structure that is so important to our understanding of the storm mechanisms.

b. *The use of tracers*

One of the weaknesses of almost all weather modification experiments is the lack of definite knowledge as to whether or not the seeding material actually reached the intended target zone, and in the desired concentration. Although one might argue that any test of effectiveness of treatment in an operational sense should also include the effects of variability in the delivery of the seeding material, a properly designed experiment should first attempt to isolate the effects in those storms known to be well treated. Since the effectiveness of any modification is thought to be related to the concentration of seeding material reaching certain parts of the cloud, it is important to examine effects as a function of the degree of seededness. Accordingly we suggest that inert tracer material be dispersed along with or as a "tag" of the active seeding agent in treated storms. Tracer materials can be selected that are easier to analyze for and have a lower background concentration than silver iodide. The tracers can be chosen to behave similarly to silver iodide particles in most respects apart from their ice nucleating ability provided they are hydrophobic, have about the same size distribution, and are generated along with the silver iodide particles using an acetone generator. Examples of such tracers are gold, rhenium, indium, iridium, osmium and tantalum.

The presence of the tracer in the precipitation from a seeded storm, or from a nominally unseeded storm in the vicinity of a seeded storm, would provide evidence that the storm was one in which the precipitation may have been affected by seeding. Similarly, the absence of the tracer in the precipitation would permit the elimination of improperly seeded storms from the allegedly treated set and would provide supporting evidence that unseeded storms in the vicinity of seeded storms were not contaminated by material from the neighboring storms. If the seededness of storms could be established in this way one could more confidently use individual storms, and indeed different periods during the lifetime of individual storms, as the units of analysis in the seeding evaluation instead of simply lumping everything together in such units as the "hail day." One could thereby avoid confounding the results from seeded and unseeded storms on a given day and simultaneously obtain an increased number of experimental units. Furthermore, by deploying seeding aircraft on all hail days and using the same tracer material without silver iodide (placebo seeding) in the unseeded situations, it should be possible to assess better whether any observed dependence of hailfall parameters on seededness (as determined from the concentration of the tracer material) could have been achieved fortuitously. The placebo approach is also useful in situations when operational difficulties prevent seeding of some storms. In the past it has been suggested that the exclusion of storms that are difficult to seed from the seeded sample would bias the sample toward the more easily treated ones. On the other hand, failure to exclude improperly seeded storms contaminates the statistics. With placebo treatment of the unseeded storms, however, we would be in a position to include such storms in both the seeded and unseeded samples.

A simple approach would be to deduce the seededness from tracer concentrations in the bulk hail and rain measured by simple collectors such as the hail rain separator used in NHRE (Nicholas, 1975). For this purpose the hail need not be kept frozen until analyzed. A statistically significant difference in the average hail parameter between placebo and actively treated storms of the same seededness category would then be the measure of the effect, either positive or negative. In this way, we could hope not only to detect an effect but also to assess the dependence of the effect on seededness. This approach might, for example, reveal increases in hail in the lower seededness categories, perhaps as a result of introducing the active nucleant in insufficient quantity or in the wrong place, or it might possibly

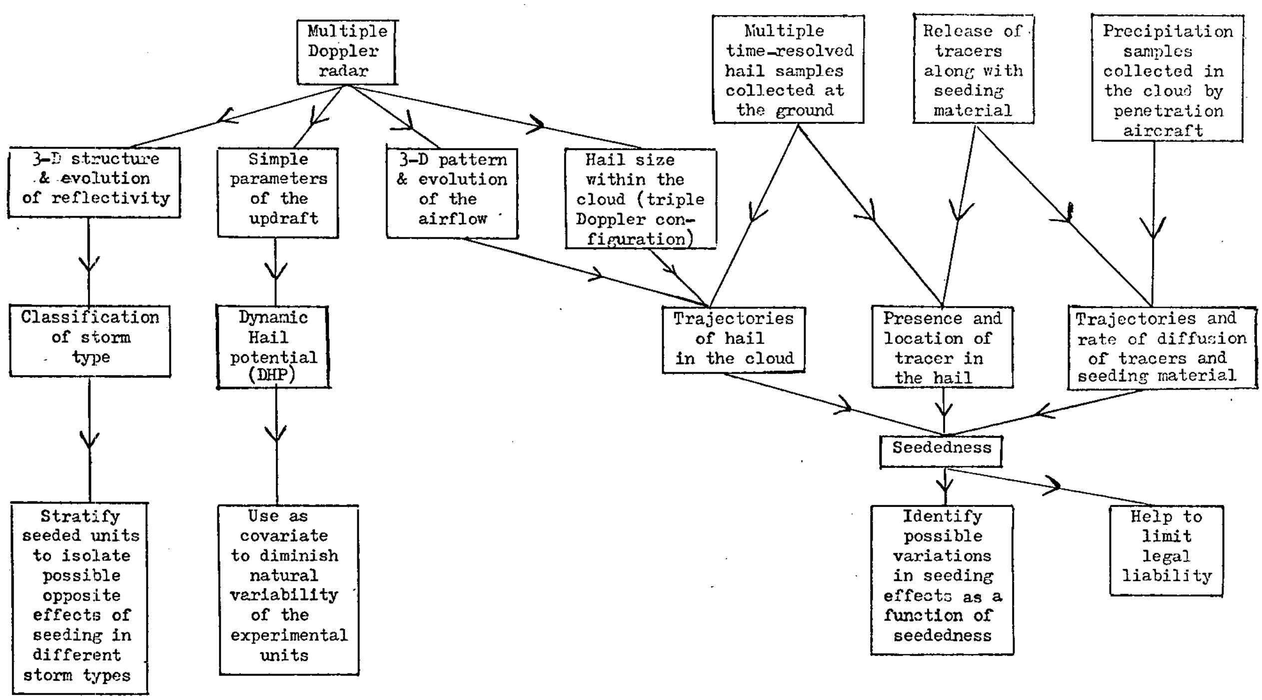

FIG. 1. Block diagram summarizing the roles of multiple Doppler radars and tracer techniques in a hail suppression experiment.

reveal a decrease in rainfall in the higher categories of seededness as a result of overseeding. Without such stratification, such positive and negative effects might mask one another and lead to a statistically inconclusive result.

The value of the simple interpretation of seededness discussed above is limited by processes such as scavenging, as a result of which the precipitation may collect seeding material that has had little opportunity to influence the hail growth. That is to say, the mere presence of the tracer somewhere in the precipitation is not by itself sufficient evidence that the seeding material played an active role in the precipitation process. To make the evidence more convincing, although still not definitive, it is necessary to undertake the more time-consuming task of measuring the radial distribution of tracer within hailstones. Tracer material found within the hailstone embryo would be evidence that any seeding material released with it is likely to have found its way into the important region where the embryo was grown. To be able to carry out this kind of study, the hailstones need to be collected in a device such as a chilled hexane bucket (Federer and Waldvogel, 1975) which would keep them frozen until retrieved.

Whether one uses tracers on a routine basis in the statistical analysis or in occasional case studies, considerable insight may be had from detailed and systematic analysis of individual stones and rain samples. The wide range of possible categories of tracer experiment has scarcely begun to be exploited. It might even be feasible to use special techniques such as ion probe microanalysis to identify single tracer-tagged silver iodide particles. Also, numerous different tracers can be used to tag the silver iodide released at different times or in different locations in the storm in order to clarify the seeding locations most likely to produce the intended effects. Along with detailed analyses of tracer content distribution within hailstones, other analyses should be carried out to determine the nature and distribution of the air bubbles, crystals, aerosols and isotopic ratio within the hailstones so as to obtain further information about their growth environment and trajectories (Macklin, 1975). One can then combine such information with the airflow and hail size measurements from the Doppler radars to obtain an internally consistent picture of the hail growth histories. Inferences from hailstone analyses alone or from Doppler radar alone are often subject to ambiguity; combined analyses, however, should narrow the range of possible interpretations. Proper exploitation of this approach places stringent requirements on the collection of large numbers of time-resolved hail samples, free from contamination, by means of elaborate fixed or mobile ground units. The logistics of collecting these hail samples is one of the most difficult aspects of the proposed experiment and far greater resources would need to be made available for this than in any previous experiment.

The use of tracers would also provide an opportunity for using storm penetration aircraft to measure the paths and diffusion rates of the tracer and seeding material. At present there is far too little information on the diffusion rates within hailstorm updrafts and we are unable to make any but the crudest estimates of the seeding rates required to produce the desired concentration in the target zone. The same penetration aircraft should also measure cloud and precipitation characteristics in order to identify directly the possible effects of seeding on the cloud microphysics in the manner achieved by Dye *et al.* (1976). One might also consider using aircraft penetrations of the anvil to investigate amounts of seeding material and the nature of the ice crystal products being exhausted into this region.

Finally, it is worth noting that the analysis of surface precipitation for the presence of tracer-tagged silver iodide may prove helpful in limiting somewhat the extent of legal liability, if such issues should arise, by providing proof of the presence or absence of seeding material in hail samples collected by individuals claiming damages.

3. Conclusions

We have stressed the great difficulties attending hail suppression experiments and have proposed two additional techniques—multiple Doppler radar and tracers—which when added to existing techniques should be particularly helpful for evaluating seeding effects and monitoring hail storm and hail growth processes. The proposals represent a radical departure from the traditional approach in seeding experiments in which the storm is treated effectively as a black box and the response to seeding of a limited number of output variables is investigated without attempting to unravel the intermediate stages. We believe the response of a storm to seeding is capable of varying in subtle ways depending on the nature of the storm and of the seeding. As summarized in the block diagram of Fig. 1, the two techniques that we propose are capable in principle of revealing some of the most critical aspects of the inner workings of the black box and its response to seeding and, at the same time, of overcoming some of the difficulties in evaluating the effects of seeding that were mentioned in the Introduction.

The field of weather modification is sorely in need of some fresh approaches. The time has come to build on the philosophy expressed in this paper and to begin designing a hail suppression experiment in which we have some chance of knowing physically what we are doing. If this paper, with all its oversimplifications, succeeds in stimulating thoughts toward this end, it will have achieved its purpose.

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