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The Paradox of Hail Suppression

Under different circumstances, cloud seeding may result in either increased or decreased hail.

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Although reports of successful hail suppression continue to appear from various parts of the world, evidence of negative effects (that is, hail increase) has been found in some programs; most experiments remain inconclusive and controversial. What is the source of this apparent dichotomy? And why is it so difficult to arrive at more conclusive and consistent results? Should the occurrence of both positive and negative effects be attributed to differences in seeding methodology as some have claimed, or to significant differences in the physical properties of the storms? These questions are explored in this article.

Hail Suppression Concepts

The basic concept underlying attempts at hail suppression is that of "beneficial competition." Thus, if one introduces a sufficient quantity of artificially induced hailstone embryos, the basic cores upon which hailstones grow, the resulting competition for the water supply among all the embryos may be so great as to prevent any from growing to large sizes and thereby allow them to melt to smaller nondamaging size. The artificial embryos are produced by seeding the cloud with an ice-nucleating agent such as silver iodide (AgI) which acts either to freeze supercooled cloud droplets and convert them to ice crystals or to grow to ice crystals from the vapor. Through the accretion of supercooled cloud water, the crystals then grow to snow pellets (that is, graupel) which constitute one form of hailstone embryo. In some storms, the nuclei may also impinge upon and freeze supercooled raindrops which then also act as hailstone embryos. In either case, the presumption behind the seeding procedure is that there is a paucity of natural ice nuclei to initiate the growth of the embryos.

Another hail suppression concept is that of "glaciation" in which the AgI is used to convert virtually all of the supercooled cloud water to ice crystals. Upon colliding with either a hailstone embryo or a hailstone, these ice crystals bounce off and so growth is impeded. However, it is generally acknowledged that this method is impractical because of the excessive quantities of AgI required to produce complete glaciation (*1*).

Some Hail Suppression Results

Among the most prominent reports of successful hail suppression are those from the Soviet Union. Although the evaluation methods used there have been questioned (*2*), their reports still claim hail reductions between 70 and 90 percent on average (*3, 4*). Notable in the recent Soviet literature, however, are admissions of the difficulty of suppressing hail in very severe storms (*2, 5*), the occasional failure of suppression efforts, and concerns about increasing hail under certain conditions (*3*). Indeed, Marwitz (*5*) noted that just one storm day accounted for 70 percent of the total hailfall of the 1972 season in the Krasnodar Anti-Hail Project in the northern Caucasus. This large fraction was due to a major storm in which suppression attempts were evidently unsuccessful. If the hailfall statistics in the Soviet Union are similar to those elsewhere in the hail-prone regions of the world, where between 50 and 75 percent of the annual hailfall occurs on only 8 to 10 percent of the hail days, then one must wonder about reports of average suppression effects in excess of 50 percent in view of the difficulties associated with suppressing the most severe storms. Thus, although we cannot ignore the Soviet claims, there are grounds for questioning the magnitude of the reported effects.

In another recent report of indications of positive suppression effects, Changnon (*6*) summarizes the "best estimates" of the results of five operational hail suppression programs as shown in Table 1. In all the projects listed except that in South Africa, aircraft flying at the cloud base were used to seed clouds with AgI. In the South Africa program new cloud towers were seeded from above with droppable AgI flares. Changnon estimates suppression effects ranging from about 20 to 48 percent based mainly on crop hail insurance data.

It is not my intent to challenge these estimates but merely to point out some of the questions about them. First, only the North Dakota pilot project was designed to include some degree of randomization in the choice of days on which cloud seeding was to be carried out. Second, all the analyses of effects were based on post hoc tests, a variety of which were tried. Moreover, the results of these statistical trials showed great variability depending upon both the test statistic and the basis for comparison (for example, relative to prior history or to adjacent unseeded areas). Most of the estimates are also based upon crop hail

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insurance records, and it is not clear how well these records reflect the areawide effects because typically only a relatively small fraction of the farms are insured, some 10 to 15 percent on a U.S. national average. Only in the South Africa project were all the farms insured. Finally, only the South Africa and western Texas projects showed significance levels better than 5 percent (that is, less than 5 percent probability of occurrence by chance). In spite of all these questions, we may regard the "best estimates" of Table 1 as suggestive of positive hail suppression effects.

Indications of success have been found with cloud-base seeding in four of the five projects listed in Table 1. These results are in contrast to the Soviet claims that a critical ingredient of their success consists of the direct injection of the nucleant "into the hail center where the nucleation and growth of hail takes place" (*7*). Davis and Mielke (*8*) also attributed the apparent success of the South Africa project to the direct injection of AgI via droppable flares on top of newly developing cloud towers and to the speed of response of the Learjet seeding aircraft in attacking those cloud turrets early in their lifetime. Indeed, the results of seeding with the slower turbocharged aircraft showed indications of increased hail damage, although these results were said to be statistically nonsignificant (*8*).

The following mixed results should also be noted. On the basis of 7 years of seeding with ground-based AgI generators in Switzerland (Grossversuch III experiment), Schmid (*9*) reported 66 percent more days with hail on days when seeding took place than when no seeding was attempted; this difference was found to be significant at the 4 percent level. Neyman's analysis of the Grossversuch III data (*10*) showed a 74 percent increase in the average number of hail reports on all seeded days, significant at the 5 percent level, and a 130 percent increase in the number of hail reports on those seeded days characterized by low-level stable layers, significant at the 2 percent level.

Grandoso and Iribarne (*11*) reported the results of ground-based AgI seeding over a 3-year period in the Mendoza area of Argentina. Without stratification of their data, they found net decreases of 34 percent in total damage (TD) and 22 percent in the average percentage damage (APD), but neither was statistically significant at acceptable levels. On the other hand, when the data were classified according to cold front (CF) and noncold front (NCF) situations, the CF data showed decreases of 79 percent in TD and 57 percent in APD, both statistically significant at the 5 percent level. The NCF data indicated increases in both TD and APD, although neither was statistically significant.

These results suggest that (i) ground-based seeding may be effective despite claims by various investigators that direct injection into the cloud base is crucial to success; (ii) seeding might produce increased hail under certain circumstances; and (iii) without some sort of physical stratification, analysis of the data may be inconclusive.

Long *et al.* (*12*) reported the results of 3 years of AgI seeding at the cloud base as part of the National Hail Research Experiment (NHRE) in northeastern Colorado. An average of 60 percent more hail mass was measured by hail-rain separators on days when seeding was carried out (16 seeded, 16 not seeded; zero values excluded) than on days when seeding was not attempted. However, the 90 percent confidence limits for the ratio of hail mass on seeded to unseeded days range from −48 to +531 percent for a log-normal fit of the data distribution. These results therefore permit the exclusion of a suppression effect in excess of 50 percent at the 5 percent confidence level. The possibility of a smaller net suppression effect cannot now be excluded with confidence.

Ulbrich (*13*), who carried out an independent analysis of the NHRE data, reported as follows:

> I have computed total storm hailfall parameters using hailstone size distributions obtained from dents in Styrofoam hailpads in the NHRE target area. Using the data for 33 days (15 seeded, 18 not seeded) on which pads were not contaminated by hailfalls on succeeding days, I have found that storm hailpad parameters are distributed among storms in such a way that those which depend on the total quantity of hailfall (e.g., total number of hailstones, total hail volume, total kinetic energy) have frequency distributions for seeded storms which are narrower and are peaked at higher values than the frequency distributions for unseeded storms. Furthermore, those parameters which do not depend on the total number of hailstones (e.g., average hailstone diameter, mean-square diameter, size spectrum variance) were found to have frequency distributions for seeded storms which were very similar to those for unseeded storms. The implication of these results is that seeding of NHRE hailstorms had little effect on the shape of the hailstone size spectrum but increased the total number of hailstones.

Ulbrich's analyses support the suggestion that in this experiment seeding probably increased the number of hailstones. However, since all the tests he used were post hoc, the results cannot be used as reliable indicators of a seeding effect, although they are strongly suggestive. Clearly, the caveat on post hoc tests is applicable to all the programs cited above.

Table 1. Changnon's (*6*) "best estimates" of hail suppression effects in operational programs.

Seasons (No.)	Area	Seeding method	Effect (%)	Basis	Primary reference
		Western Texas			
4	Two counties	Cloud base	−48	Crop loss cost* compared to prior history	(*38*)
		Southwestern North Dakota			
15	Two counties	Cloud base	−31	Crop hail insurance rates compared to adjacent unseeded counties	(*39*)
7	Four counties				
		North Dakota pilot project			
4	One county	Cloud base	−30	Composite of hail characteristics, radar, and crop loss data	(*40*)
1	Three counties				
		South Africa			
4½	5300 hectares	Cloud top	−23†	Crop severity ratio‡ compared to previous history	(*8, 41*)
		South Dakota			
4	50 to 70 percent of state	Cloud base	−20	Crop loss cost compared to prior history	

*Crop loss cost = (dollar loss/dollar liability) × 100 percent. †Changnon reports a value of 40 percent; however, the primary references report about 23 percent. ‡Crop severity ratio is the average percent loss over the area hit.

Some Physical Reasons for Increased Hail

There are a variety of physical reasons why seeding might increase hail under some circumstances. This result could occur whenever the supply of supercooled water for hailstone growth exceeds that which can be effectively depleted by the total number of natural and artificially produced embryos. Obviously, there must be some critical combination of supercooled water supply and embryo concentration such that the introduction of additional embryos will cause competition among all of them for the water so that none grow large and thus can melt substantially as they fall through the warmer layers. Whenever this critical combination is not attained, however, seeding may simply increase the number of hailstones. This can occur under the various circumstances described below.

The following discussion is admittedly qualitative, but no more so than the treatments purporting to favor hail suppression. I shall also refer to numerical models; such models also involve a considerable degree of subjectivity in basic assumptions.

Supercell storms. A vertical cross section of a typical supercell storm, as depicted by Browning and Foote (*14*), is shown in Fig. 1. Once it grows to maturity, the storm may continue in an essentially steady state for several hours. The airflow shows a strong tilted updraft entering the storm on its forward (southern) side. This updraft generates and carries an abundant supply of cloud water which may remain supercooled at very low temperatures. Where the updraft is strongest, the cloud particles are carried up so rapidly that they have insufficient time to grow to the size of precipitation elements and so they produce only weak or undetectable radar echoes. This small size of the cloud particles is responsible for the weak echo vault (Fig. 1). On the flank of the updraft where the vertical velocities are weaker, cloud particles do have sufficient time to grow to precipitation sizes either in the form of supercooled raindrops or snow pellets. These become the embryos of the larger hailstones and are found in the so-called "embryo curtain" (Fig. 1). Once they have grown to sufficient size, the embryos are believed to fall out but are caught up once more in the updraft and are recycled. This time they are carried up along a trajectory close to the lower boundary of the weak echo vault (as shown by the short arrows in Fig. 1), grow rapidly upon the supply of supercooled water in the updraft, and fall out as large hail on the northern side of the vault.

Browning and Foote (*14*) have pointed out that in such storms the supply of supercooled water in the region of the strong updraft and weak echo vault is very large. The embryos that become the largest hailstones are those that are carried over the top of the vault near the bottom of the overlying radar echo where they are the first to encounter the large supply of supercooled water and can remain in close balance with the updraft velocity for extended periods. In this case, the introduction of additional embryos is likely to produce more hail rather than less because no realistic number of embryos can consume the abundant water supply. This hazard has been elucidated by Browning (*15*) and Browning and Foote (*14*), who also discussed other possible approaches toward seeding supercells.

The frequency of occurrence of supercell storms is not yet well known. However, in northeastern Colorado about 8 percent of the hail days account for about 50 percent of the annual hailfall (*16*). Browning (*15*) suggests that the days with the greatest hailfall are those on which supercells occur. A quantitative study by S. P. Nelson (*17*) bears this out in the case of Oklahoma storms. Thus, the seeding of a few such storms may result in significant increases in total seasonal hailfall.

Cold-cloud base, graupel embryo storms. Using a one-dimensional, time-dependent, microphysical model, L. D. Nelson (*18*) has conducted numerical simulations of rain and hail growth and the effects of seeding. The primary results indicate that the seeding of storms having cold cloud bases (less than about 8°C) generally produces increased hailfall. The effect varies with the vigor of the updraft and the total depth of the cloud, but Nelson found increases in hail up to 46 percent with meteorological radio soundings typical of the vertical temperature and humidity profiles of northeastern Colorado and Montana, even with massive seeding rates. On the other hand, decreased hail (and rain) were found with the very warm base clouds common to the St. Louis area in summer. Such clouds produce supercooled raindrops which can be readily frozen on

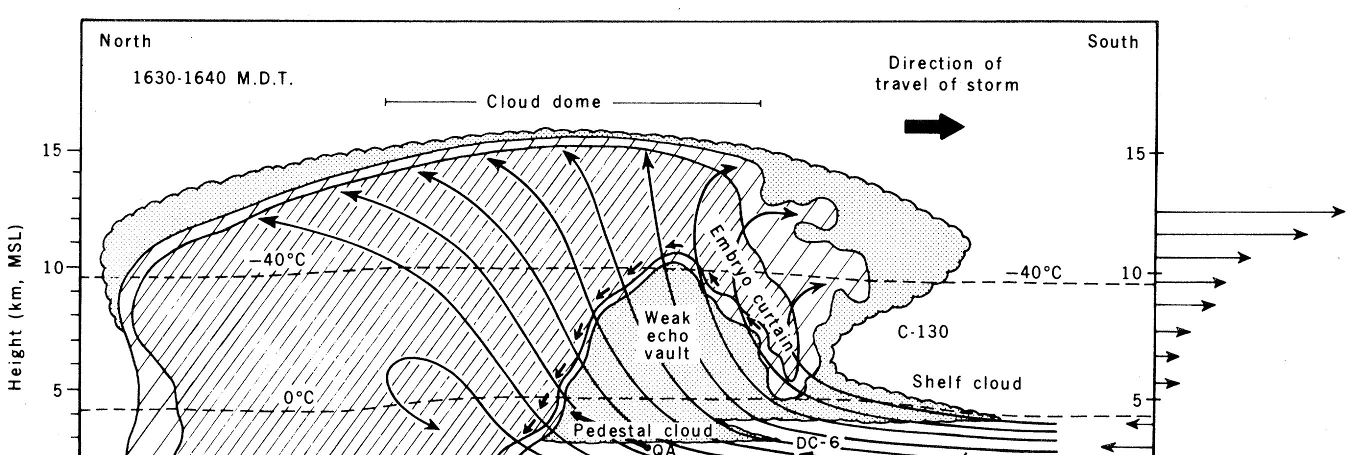

Fig. 1. Vertical section in a plane oriented from northwest (340°) to southeast (160°), showing features of the visual cloud boundaries of the Fleming, Colorado, supercell storm at 1630 to 1640 M.D.T., 21 June 1972, superimposed on the pattern of radar echo. The section is oriented in the direction of travel of the storm. Two levels of radar reflectivity are represented by the different densities of hatched shading. Areas of cloud devoid of detectable echo are shown stippled. Short, thin arrows skirting the boundary of the vault represent a hailstone trajectory. The thin lines are streamlines of airflow relative to the storm drawn to be consistent with the other observations; *C-130*, *DC-6*, *QA*, and *B* signify positions of airplanes. To the right of the diagram is a profile of the wind component along the storm's direction of travel, derived from a Sterling, Colorado, sounding 50 kilometers south of the storm. [From Browning and Foote (*14*)]. [Courtesy of the *Quarterly Journal of the Royal Meteorological Society*, London]

contact with AgI nuclei and thereby generate abundant competing embryos.

L. D. Nelson attributed the increased hail that resulted from the seeding of cold-base storms to the fact that their hail embryos are graupel. In such cases, the ice nuclei are used inefficiently since crystal activation occurs mainly from the vapor at the higher and colder levels, thereby resulting in small crystals. These crystals may be lost by detrainment from the cloud boundaries and by blowoff in the cloud anvil, the flat layer-like cap of a thunderstorm which may extend many miles out ahead of the main storm core. Moreover, the potential for growth of these crystals to graupel by riming (that is, the accretion and freezing of supercooled cloud droplets) is greatly reduced by their location above the main region of supercooled water. However, some of these crystals do become large enough, soon enough to be effective hail embryos, but these are so few that they do not compete significantly for the water. Thus, they grow like the natural embryos and increase the total number of hailstones. Of course, in colder situations they may survive the fall to the surface without excessive melting.

Farley *et al.* (*19*) have also conducted a numerical simulation of the seeding of a cold-base storm characteristic of northeastern Colorado. In contrast to L. D. Nelson, they found substantial reductions in both hail and rain when their model storm was seeded. Orville (*20*) attributes the difference in results to the fact that in the model of Farley *et al.* seeding is assumed to cause the conversion of supercooled cloud water to submillimeter-sized graupel particles capable of competing with the natural particles at an earlier stage and lower altitude than in the L. D. Nelson model. The reality of the differing growth processes needs to be determined by in-cloud observations.

In any case, the findings of L. D. Nelson raise the critical question of whether the relatively large supercooled drops are found in the typical cold-base clouds of northeastern Colorado. The observational evidence is conflicting. For example, using data obtained from sailplane penetrations, Cannon *et al.* (*21*) found that water droplets larger than 100 micrometers in diameter are extremely rare above the 0°C level in the convective clouds in this area. Moreover, Dye *et al.* (*22*) found that observed radar reflectivities were consistent with the sizes and concentrations of graupel particles collected during the sailplane penetrations of small cumulonimbus clouds. However, Musil *et al.* (*23*) report significant amounts of liquid drops several millimeters in diameter at the −12°C level in the updrafts of newly developing cells.

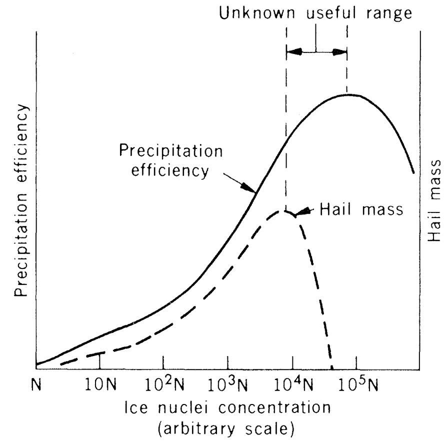

Fig. 2. Schematic diagram of the general variation of precipitation efficiency and hail mass as a function of ice nuclei concentration. All scales are arbitrary.

These apparent conflicts may be due to the differences in the populations of cloud condensation nuclei (CCN) entering the various clouds. A large concentration of CCN would activate many cloud droplets of nearly uniform size and thereby impede their growth by coalescence to raindrop size. In these clouds, commonly referred to as continental clouds, ice crystals are activated prior to the growth of raindrops and graupel particles predominate. On the other hand, clouds with smaller CCN concentrations, smaller cloud droplet concentrations, and a broader size spectrum are referred to as maritime clouds. Under maritime cloud conditions, cloud droplets can grow to raindrop size. The latter process would also be enhanced by weaker updrafts in the lower regions of the cloud which would allow longer times for the coalescence process to operate.

Such arguments suggest that one critical factor that determines whether a storm responds positively or negatively to seeding is whether the hailstone embryos are frozen drops or graupel. Knight *et al.* (*24*) found that about 85 percent of the hailstones collected in Colorado have graupel embryos. In addition, Knight and Knight (*25*) reported a notable tendency for the proportion of frozen drop embryos to increase at warmer cloud-base temperatures. Accordingly, they also found a predominance of frozen drop embryos in the hail of Oklahoma where cloud-base temperatures are warmer than in Colorado and where the CCN and cloud droplet concentrations are also thought to be smaller (that is, more maritime) than those characteristic of Colorado. Marwitz (*5*) also quotes the observation of U. Khorguani that hailstones in the Soviet Union contain mainly frozen drop embryos.

Dennis (*26*) arrived at a conclusion very similar to that of L. D. Nelson (*18*) through simpler physical arguments. He concluded that "the ease with which hail can be suppressed in a more persistent cloud depends upon whether or not the cloud water passes through an intermediate rain phase or whether it is frozen directly to the growing hailstones." His key point was that a large raindrop sweeps out a volume of roughly 1 liter sec^{-1}, so that, once crystals a few micrometers in diameter reach concentrations in excess of 1 per liter, the drops will be frozen quickly. He thus attributed the apparent success of the Soviet hail suppression efforts to the freezing of supercooled raindrops.

Another factor that needs to be emphasized is the great efficiency with which ice nuclei operate in clouds containing supercooled raindrops. When cold raindrops are present, not only is the collection rate of nuclei greatly increased but the freezing of one raindrop causes it to warm to 0°C and thereby produces large supersaturations (about 0.5 percent) in a surrounding wake several hundred cubic centimeters in volume. This supersaturation then activates a vast number of nuclei in the drop wake region, thus greatly increasing the chance of contact freezing of other raindrops and propagating the effect in a rapid chain reaction (*27, 28*). Gagin (*29*) has also emphasized the importance of this process. Clearly, there is no corresponding mechanism at work in "cold" clouds in which the water phase is restricted to cloud size particles and the precipitation elements are graupel.

Other processes leading to increased hail. There are undoubtedly a variety of other mechanisms by which seeding may lead to increased hail. Two deserve mention here: (i) Dennis and Musil (*30*) have found increased hail sizes in a numerical model of seeding effects when artificial glaciation occurs with strong updrafts which reach their maxima not far above the freezing level. In such cases, the hailstones grow more rapidly upon an ice-water mixture than they would upon supercooled water alone. (ii) Since the maximum hailstone sizes have fall speeds closely related to the maximum updraft velocities, any process that increases the updraft speed may also increase the hail size. Hail size will also be increased if the peak of the updraft profile is altered so as to bring it within −20° to −30°C. In this temperature region the rate of heat dissipation by the hailstone and the water collection rate are such as to permit the accreted supercooled water to freeze most readily. At colder temperatures, growth is slower in the smaller liquid water environment; at warmer temperatures, the collected water is unable to freeze entirely. Although Dennis and Musil (*30*) explicitly discussed the latter phenomenon, they failed to mention the possibility that seeding could either increase the updraft strength or alter the position of its peak through the release of additional latent heat as a result of the artificially induced freezing. Farley *et al.* (*19*) explicitly referred to such effects.

Thus, although there are circumstances under which seeding may decrease hail under certain conditions, there are other situations under which seeding may result in more hail. At least two of these conditions (that is, supercells and graupel embryo clouds) are dominant in northeastern Colorado where the data of the NHRE appear to indicate that more hail occurs on seeded than unseeded days. These findings also provide possible explanations for the apparent successful results (on average) in the Soviet Union and also for their occasional failures, as well as for the distinction between positive and negative effects in Switzerland (*9*) and Argentina (*11*) with various meteorological stratifications.

Some Implications for the Future of Hail Suppression

The preceding discussion has important implications for the future of weather modification generally and for hail suppression in particular. Some of these implications have been obscured in part by the early encouraging results in some parts of the world, by implicit pressures for positive results, and by the difficulty of recognizing and admitting negative results in some programs when others are claiming such drastic positive ones.

Indeed, this dilemma has characterized many efforts to modify weather. When positive results are obtained, even at inadequate levels of statistical significance, the unconscious bias of the investigator or the operator inclines him to put them in the best possible light. On the other hand, when negative results are found, there are two common reactions: (i) to search far and wide for physical or statistical reasons to account for them, a process which frequently succeeds in a plausible if not entirely true explanation; or (ii) to attribute them to inadequate or inappropriate methods. And since there is in principle an infinity of methods, negative results can almost always be discounted. In conducting an objective experiment it is therefore of utmost importance to identify in advance the physical processes that are likely to produce either positive or negative effects and to design the experiment in such a manner that effects of both signs may be discriminated according to the physical conditions present.

More specifically, the recognition of the probability of both positive and negative effects implies that (i) the results achieved and the methods used in one kind of storm are not necessarily transferable to others and (ii) the statistical conclusiveness of a randomized seeding experiment may be jeopardized if positive and negative effects are counterbalanced so that real effects of both signs may be masked unless the storm conditions are stratified in a rational physical system.

A First Approach to Physical Stratification

In what follows, I attempt to develop a rational scheme of physical stratification. As a point of departure, let us examine the schematic diagram of Fig. 2 which illustrates the possible behavior of both the precipitation efficiency of a storm (the ratio of total precipitation output to total moisture input) and its production of hail as a function of the ice nuclei (IN) concentration introduced into the storm updraft at the cloud base. The IN scale is arbitrary because information on the actual dependence of either variable on IN is almost entirely lacking. I believe that the general behavior of both curves is reasonable except in the case of maritime clouds which may precipitate without going through the ice phase. In any case, even if one questions the validity of portions of the following arguments, they do illustrate several potentially important concerns which appear to have been ignored in the past.

The precipitation efficiency is thought to increase with the concentration of both CCN (which is not explicitly shown in Fig. 2) and IN. However, once the combined nuclei concentration exceeds some critical level, so many cloud droplets and ice crystals are activated that they remain small and are carried up by the draft to be exhausted and lost by evaporation in the anvil (*31*). Beyond this point the precipitation efficiency must therefore decrease with increased nuclei input.

Similarly, the number of hailstones, and thus their total mass, must first increase with IN concentration until the number reaches such large concentrations that the competition for water among the hail embryos exceeds the supply, none grow large, and they melt upon falling to the ground. Indeed, this is the goal of hail suppression. However, two critical problems are evident.

The first is that we do not know the relative positions of the peaks in the two curves, nor are they likely to be independent of the updraft and cloud water supply. However, if we should seed sufficiently to decrease the hailfall, this might correspond to a position to the right of the maximum on the precipitation efficiency curve and thus decrease the total precipitation reaching the ground. Obviously, decreases in rainfall during the growing season are unacceptable in the U.S. high plains and elsewhere. For example, Borland and Snyder (*32*) have shown that a 5 percent decrease in rainfall negates the economic benefits of a 20 percent decrease in hail damage. Thus, there is some unknown, economically useful range of nuclei concentrations, roughly between the peaks of the two curves in Fig. 2, in which hail suppression would be effective.

The second problem is that, since we generally have no knowledge of the natural IN concentrations entering the storm, particularly in the case of convective storms where wind-blown dust may dominate the IN spectrum (*27*), we do not know the net IN concentrations produced by seeding. Combined with the probable variability in the position of the peak, it seems likely that seeding may produce either more or less hail than would occur naturally. Obviously, there is a need to measure the natural IN concentrations entering the storm at the cloud base in both seeded and unseeded storms and to stratify the hail output accordingly. In addition, we need to measure the rate of water supply in order to locate the variable position of the peak of the hail mass curve. We also need to know the IN output of the seeding devices.

In light of my earlier discussion of the probable increase in hail in supercell storms and the generally accepted findings that ordinary single cell or multicell storms are more responsive to seeding (*15, 33*) than other storm types, the data must also be stratified according to storm type. In view of the findings of L. D. Nelson (*18*) and Dennis (*26*) concerning the relation of cloud-base temperature and type of hail embyro to the storm's response to seeding, these factors must also be considered important stratification variables. However, they are probably not independent of one another.

The results of the numerical modeling studies by Dennis and Musil (*30*) and the empirical work of Maxwell (*34*) strongly indicate that the maximum hail size is closely related to the maximum updraft intensity and the temperature at that height. Browning and Atlas (*35*) have proposed that these be combined to form a single parameter called "dynamic hail potential" or DHP. They suggest also that the DHP be determined by dual Doppler radar, which can be used to measure the actual horizontal and vertical air motions.

Danielsen (*36*) has listed nine variables which he believes exert a strong influence on hail production. Most of these are similar or related to those mentioned here. However, he also placed some emphasis on the specific humidity at the cloud base and the magnitude and scales of turbulence. Unfortunately, our knowledge of turbulence within the hail growth zones is sparse, and it seems unlikely that we will have the means to observe it routinely for some time. Moreover, there are proxy variables which may be substituted for some of those mentioned that may be more readily measured.

In an initial list of stratification variables, I would include: (i) the natural IN concentration in the storm inflow region at the cloud base; (ii) the IN seeding rate; (iii) the cloud-base temperature; (iv) the type of hail embryo; (v) the storm type; and (vi) the dynamic hail potential. The problem becomes one of how to combine the set of variables into a single stratification variable which relates to hail production. The logical way to attempt such a combination is through numerical modeling in the manner of Danielsen *et al.* (*37*), Dennis and Musil (*30*), or L. D. Nelson (*18*), or with one of the progressively more realistic two-dimensional models. Although no existing numerical model can adequately simulate the three-dimensional complexities of a supercell storm, models should nevertheless permit the development of an array of storm classes which may be organized in a logical physical fashion.

Figure 3 illustrates schematically one possible outcome of a randomized seeding experiment in which the total hail mass (or some other test variable) is measured as a function of the combined storm stratification class number. The curves have been drawn with roughly equal areas to emphasize that there may be no difference in the mean hail production as a result of seeding. Yet there are two important ranges in which dramatic effects are indicated in this speculative

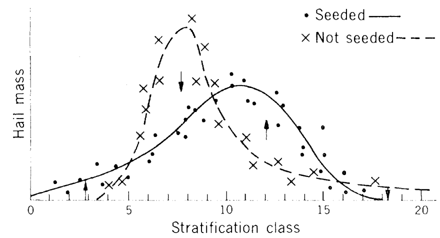

Fig. 3. Schematic diagram of the possible outcome of a randomized seeding experiment in which the hail mass is stratified by physical classes.

example: a major hail suppression effect is shown in classes 5 to 9, whereas increased hail is found in classes 9 to 16. In other words, without stratification the investigators would have concluded either that seeding had no effect or that any effect was not statistically significant. With stratification, however, there is at least the hope of discriminating between real positive and real negative effects which otherwise would have masked one another.

It is not possible to predict in advance the number of samples that would be required to reach statistically conclusive results in an experiment of this sort; that would obviously depend upon the differences in magnitude and shape of the fitted curves for seed and no-seed cases. We do know, however, that without stratification the number of years required to detect an effect of realistic magnitude is very large indeed. For example, Long *et al.* (*12*) showed that the detection of an average hail suppression effect of 25 percent with adequate confidence may require at least several decades in northeastern Colorado. Clearly, since we now have abundant physical reasons to expect seeding to result in either increased or decreased hail under different circumstances, the only realistic hope for reaching meaningful conclusions through a randomized experiment is to employ rational physical stratification. Of course, such an experiment would be substantially improved and its duration reduced if we were to find strong predictor variables or covariates which account for a significant fraction of the natural variance in hailfall. Two approaches toward the latter end have been proposed by Browning and Atlas (*35*).

Ultimately, our goal should be to predict the behavior of both the solid and dashed curves in Fig. 3 through realistic numerical models. In any case, if we should be able to attain results such as those in Fig. 3, we would also learn a great deal more about the physical mechanisms in operation, and also we could discover how to alter our seeding "recipes" to further enhance the beneficial effects and minimize the deleterious ones.

Summary and Conclusions

Reports of successful hail suppression continue to come from the Soviet Union, South Africa, and a variety of other operational programs in the United States. Although the project designs and methods of data analysis in all these programs suffer from deficiencies which raise doubts about the validity of the reported results, the cumulative evidence appears to suggest that hail suppression is feasible under certain circumstances. On the other hand, reports of occasional failures in the Soviet Union, of negative results in Switzerland, indications of both positive and negative results in Argentina, and suggestions of negative effects in the preliminary findings of the NHRE in the United States also appear to suggest that there are a variety of conditions in which seeding results in increased hail.

Until now there has been a tendency to attribute this apparent dichotomy to differences in seeding methodology and rate. However, both positive and negative results, or strong indications thereof, have been found with a variety of methods including ground-based and cloud-based generators, flares dropped from above the cloud top, and direct injection by rockets and artillery.

There are at least four physical mechanisms by which seeding may produce increased hail. Two of these occur in situations in which the rate of supply of supercooled water exceeds that which can be effectively depleted by the combination of natural and artificially produced hail embryos. This may occur in supercell storms and in any cold-base storm in which the embryos are graupel rather than frozen raindrops. Moreoever, present seeding methods are much more effective in warm-base situations in which the hail embryos are frozen raindrops. Increased hail is also probable when partial glaciation of a cloud is produced and the hail can grow more effectively upon the ice-water mixture than upon the supercooled water alone. Similarly, increases in the amount of hail may occur whenever the additional latent heat resulting from nucleation alters the updraft profile in such a manner as to increase its maximum velocity or to shift the peak velocity into the temperature range from −20° to −30°C where the accreted water can be more readily frozen. A probable associated effect is the redistribution of precipitation loading by the combination of an alteration in the updraft velocity and the particle sizes such that the hail embryos may grow for longer durations in a more favorable growth environment.

The probability that seeding may produce both positive and negative effects implies that: (i) the results achieved under one set of conditions or in one part of the world are not necessarily transferable to other conditions or meteorological regimes; (ii) without rational physical stratification of the data, a randomized statistical experiment may be statistically inconclusive because of the balancing positive and negative effects; (iii) without such stratification, we will probably be unable to improve our seeding methodology or "recipes" to optimize the beneficial effects and minimize or avoid the deleterious ones; and (iv) hail suppression programs may be jeopardized by legal injunctions against potentially hazardous activities or claims for damage unless some form of insurance can be provided or means are found to avoid the hazardous situations.

In order to enhance the chances of success of a statistical experiment, I propose a first approach to a scheme of stratification which should permit the physical discrimination between the conditions leading to increased or decreased hail. The strength of a statistical experiment would also be enhanced and its duration reduced by the use of a strong covariate; dynamic hail potential is one of the most likely candidates.

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Analysis of Living Tissue by Phosphorus-31 Magnetic Resonance

Phosphorus nuclear magnetic resonance is a new method for observing the internal milieu of intact cells.

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Nuclear magnetic resonance (NMR) spectroscopy, originally a tool of the physicist and then, for more than a score of years, one of the most potent analytical methods of the chemist, has, within the last 10 years, found extensive application in the field of biochemistry (*1*). The growing use of the method has been principally stimulated by technological advances, which have steadily improved the spectroscopic sensitivity, permitting virtually every element of the periodic table to be experimentally accessible on a practical level.

It was inevitable that the method would eventually find application in the field of physiology, and this, in fact, is the principal new application of NMR technology in the 1970's. The use of NMR in the study of living tissues is at once simple and complicated—simple, in that the analysis of a piece of tissue is straightforward and requires little specialized equipment; complicated, in that the interpretation of the data poses a host of empirical and theoretical problems.

Our applications of NMR in basic biomedical research have involved detection of the phosphorus-31 nuclide, which, at 100 percent natural abundance, is the common isotope of elemental phosphorus. These studies (*2–21*) and those of others (*22–35*) conducted elsewhere have demonstrated that high-resolution ^{31}P NMR spectra of high information

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