Cloud Seeding: One Success in 35 Years

After three decades of promise and disappointment, weather-modification researchers are learning that there are no easy shortcuts

It all started on a hot July day in 1946 in one of those new home freezing units. In his laboratory at the General Electric Company, Vincent Schaefer serendipitously discovered that a bit of Dry Ice could create a virtual snowstorm in a freezer that until then had contained only a fog of cold water. If it worked in a freezer, many reasoned, it should work in clouds to tame storms and make rain.

In what must have been the most audacious scaling up of a laboratory experiment ever attempted, a group of government and private researchers performed the home freezer experiment little more than a year later on a full-fledged hurricane east of Jacksonville, Florida. The storm promptly changed course (probably of its own accord) and smashed into Savannah, Georgia.

The same hard lesson has been repeated many times since: do not fool with something you do not understand. The hazard for researchers during the past 35 years has not been so much the weather itself as their repeated failures to prove early claims that they could change the weather. Clearing airports of cold fog proved to be easy enough, but proof of the ability to increase rain or snow eluded researchers for 30 years. Today, only a single set of experiments, which were conducted in Israel, appears to have confirmed an increase in precipitation after cloud seeding. The results of a few other experiments seem encouraging but hardly convincing. Both the one apparent success and the failures demonstrate that weather-modification experiments require statistical rigor as well as some idea of how clouds work if researchers are to overcome the confounding natural variability of the weather.

"The Israeli experiment," says Roscoe Braham, a meteorologist at the University of Chicago, "is the only experiment that has consistently proved to have yielded increases in rain at the ground; no other project has shown consistent results." The first of two Israeli weather modification experiments ran from 1961 to 1967 under the direction of three researchers from the Hebrew University of Jerusalem—Abraham Gagin, Jehuda Neumann, and Ruben Gabriel, who is now at the University of Rochester. They wanted to determine whether seeding wintertime clouds with fine particles of silver iodide would increase rainfall over northern Israel. They assumed that many Israeli clouds could yield more rain if silver iodide were added to them to promote the formation of ice particles from water droplets cooled below the freezing point, the first step in the precipitation process. The Israeli I experiment appeared to have succeeded. Rainfall, according to a number of independent analyses, increased about 15 percent in the target areas after cloud seeding. That is a respectable amount in rainmaking circles.

In fact, the Israeli researchers were even more successful than the reported analyses suggested. The project had a quiet start, Gabriel recalls, for fear that word of their work would leak out to less than friendly Arab neighbors downwind of the seeding target areas. If more rain fell on Israel, would less fall on Jordan? Apparently not. Glenn Brier, Louis Grant, and Paul Mielke of Colorado State University (CSU) analyzed rainfall records from Lebanon, Syria, and Jordan available through routine international data exchanges. They did find downwind seeding effects outside of Israel's borders, but the effects were rainfall increases of perhaps 20 to 30 percent; they found no evidence of any decreases.

The primary purpose of the second, 1969–1975 Israeli experiment was to see if seeding would enhance rainfall over the drainage system that supplies water to the Sea of Galilee (also known as Lake Kinneret). The Israelis captured about half of this catchment area, including the Golan Heights, during the 1967 war. As it turned out, Israeli II also served as a confirmatory experiment; that is, one in which specific hypotheses are tested and a strict design is adhered to throughout in order to confirm an apparent effect of a preceding, exploratory experiment. Only in the late 1970's did the concepts of exploratory and confirmatory experiments become formally accepted among weather-modification researchers, and then only at the insistence of statisticians (*Science*, 24 November 1978, p. 860).

The strict design of Israeli II, plus some luck at having such cooperative clouds, seems to have paid off. According to recent analyses by the experimenters (*1*), precipitation increased 13 percent in the target area as a whole and 18 percent in the smaller catchment area. The probability that the increase resulted from a chance distribution of particularly rainy days was 2.8 percent for the whole target area and 1.7 percent for the catchment area. That compares with the approximate significance level of 40 percent for the recently analyzed Florida Area Cumulus Experiment (FACE-2), an unsuccessful attempt to confirm FACE-1 (*Science*, 16 July, p. 234). The significance level could only be lowered to 13 percent by dropping a day of heavy rainfall without seeding, which would have been a violation of the rules of a confirmatory experiment.

Israeli II seems to have avoided such statistical problems, in part by accumulating 388 experimental days (days on which a random decision to seed or not to seed would be made) compared with FACE-2's 51 days. Having such a small sample, FACE-2 experimenters tried to minimize the impact of naturally rainy days by predicting and eliminating them before the designation of experimental days. Among other problems, one such day slipped through. The Israeli experimenters could afford the luxury of rejecting only days obviously lacking suitable clouds; their large sample would not be greatly influenced by a few particularly rainy days, they reasoned. They could also compare the rainfall in the target area with natural rainfall on the same day in a control area upwind of the seeding area. This allowed them to account for all but one-third of the random natural variability in the target area, according to Gabriel. In the FACE target area of south Florida, the summer rain is too spotty to allow the use of a control area, he believes.

The Israeli II data must still be reanalyzed by other statisticians, but most researchers are also impressed that the results make so much physical sense. The clouds that Gagin and Neumann hypothesized would be most susceptible to seeding did indeed produce the most additional rain after seeding. They reasoned that, because silver iodide is not

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very efficient at temperatures warmer than −5°C and clouds colder than about −20°C initiate the precipitation process quite well on their own, the best seeding targets would be clouds whose tops were between −15° and −20°C.

In fact, seeding had little effect on days when the modal value of cloud-top temperatures was warmer than −10°C or colder than −21°C. When cloud-top temperatures were between −15° and −21°C, rainfall increased 46 percent, significant at the 0.5 percent level. Apparently, many of the Israeli clouds never grow high enough to reach the cold temperatures needed to freeze supercooled water in the absence of silver iodide.

No other precipitation enhancement experiment enjoys the widespread, albeit tentative, acceptance that Israeli I and II do. Further analysis, as additional details become available, may strengthen that support, but in the complex and often poorly understood science of weather modification popular acclaim can be a fleeting thing. The Climax experiment is a case in point.

Researchers at CSU headed by Louis Grant carried out the Climax II experiment between 1965 and 1970 to confirm apparent snowfall increases from seeding in the Dillon and Leadville area of the Colorado Rockies during the earlier Climax I experiment. The situation there appeared to be similar to that of the Israeli experiments—some of the winter clouds encountering the high Rockies were assumed to be cold, but not cold enough to produce many natural ice particles. Seeding with silver iodide should help, and statistical analysis of Climax II did show an 18 percent increase significant at the 13 percent level. Combined data from Climax I and II showed an increase significant at the 6 percent level. Seeding also seemed most effective at warmer cloud temperatures, as expected. Everything looked fine.

When CSU researchers later performed accessory analyses of the impact of seeding outside the target area, they found a serious problem. On days when clouds were seeded, more snow fell everywhere—not only in the target area but also far beyond it in all directions. Apparently, days randomly chosen for cloud-seeding also happened to receive more natural snowfall than experimental days that were not scheduled for cloud-seeding, a rather improbable event considering the total of 372 experimental days involved.

In their recent reanalysis (*2*), Paul Mielke and other CSU group members adjusted for this natural variability of snowfall by comparing the measured snowfall at stations in the target area with snowfall on the same days at adjacent control stations. This reanalysis decreased the apparent snowfall enhancement for Climax II from 18 to 9 percent, but it also reduced the probability that the increase resulted from sheer chance from 13 to 1 percent.

Perhaps the biggest problem for the CSU reanalysis is the necessity for any reanalysis at all. Strictly speaking, researchers planning to conduct a confirmatory experiment must specify the method of analysis beforehand; if that method does not produce a convincing result, the experiment fails to confirm earlier suggestions of a positive seeding effect. Mielke argues that the Climax

A Few Lessons Learned

The history of weather modification is replete with lessons to be borne in mind by researchers.

• *Project Whitetop*. In the late 1950's, commercial rainmaking was commonplace, as were claims of successful rainmaking. The aim of Project Whitetop, under the direction of Roscoe Braham of the University of Chicago, was to prove or disprove these claims in the case of summer convective clouds in the Midwest. Conducted over south-central Missouri, this was one of the first sophisticated studies of weather modification.

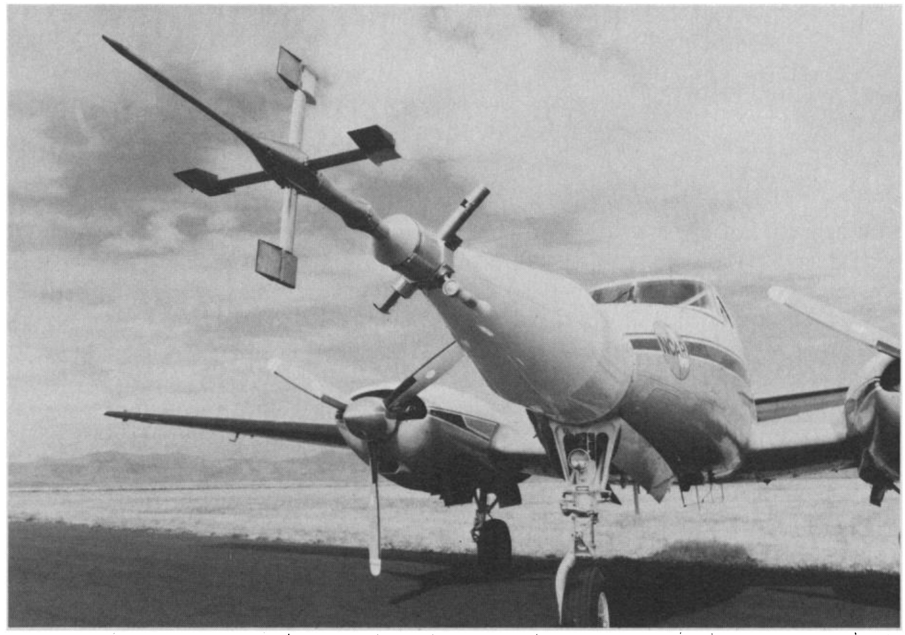
The net effect of the seeding during five summers was a decrease in rainfall. The best explanation seems to be that the Missouri clouds had all the natural ice particles they needed to begin precipitation. Seeding only created an excess of very small ice particles that tended to remain suspended in the cloud rather than fall as rain.

• *National Hail Research Experiment*. Soviet scientists had an interesting idea. In the 1960's, they were claiming 60 to 90 percent reductions in hail by seeding. American researchers visited the Soviets to learn more. The evidence was "hardly viewed as conclusive" by American scientists, recalls Brant Foote of the National Center for Atmospheric Research, but "it was clear that somebody over there believed it."

American researchers began the 5-year National Hail Research Experiment in 1972 to check the Soviet claims, but halted it after only 3 years because they could already see that they had not produced the claimed hail reductions. Seeded hailstorms actually produced more hail than those that were not seeded, although the increase was not statistically significant. More damning, though, was the discovery that a zone of accumulated supercooled water, which was essential to the Soviet's hypothetical mechanism for reducing hail, simply did not exist in the American clouds. A recently completed Swiss experiment in which the Soviet methods were exactly duplicated reportedly also failed to show any reduction in hail.

• *Project Stormfury*. It was a bold idea—to seed the clouds just outside of the eye of a hurricane, invigorate their circulation, and thus snuff out the strongest winds of the storm on the edge of the eye. Researchers seeded three hurricanes in the 1960's, two of them under the formal Stormfury program. The winds of Hurricane Debbie in particular dropped and then regained their strength after each of two seeding forays. Some researchers took that as encouraging support for the Stormfury hypothesis.

"The scientific assumptions of the Stormfury hypothesis just were not verified by the studies of the past 5 years," says Stanley Rosenthal, director of the National Hurricane Research Laboratory in Miami. "Maybe the idea was just 20 to 30 years too soon." The idea had been to promote the freezing of liquid water droplets to ice; the heat released would then invigorate the growth of the seeded clouds. Stormfury researchers did not know, until better airborne instrumentation became available in the mid-1970's, that the opposite conditions existed in the seeded clouds—plenty of ice and little liquid water. In addition, the behavior of Hurricane Allen of 1980 showed that even the winds of unseeded storms can fluctuate the way Debbie's did. "We're learning that hurricanes are a lot more complicated than people in the 60's thought," says Rosenthal. In light of these developments and obvious NOAA budget problems, Project Stormfury was recently terminated.—R.A.K.



NCAR

Cloud physics instrumentation

Airborne instrument platforms developed in recent years have been crucial to understanding what really happens inside clouds during seeding. This Beechcraft Queen Air, equipped here for the Cooperative Convective Precipitation Experiment (CCOPE) performed over eastern Montana in 1981, is even more heavily instrumented than it appears to be. The vanes, in combination with pressure sensors in the tip of the boom and an inertial navigation unit, measure turbulent fluctuations of the air. The three other instruments on the nose measure rapid fluctuations in temperature and humidity. Less obvious instruments measure ground temperature, precipitation, and liquid water.

researchers designated the control stations and the effective temperature ranges before Climax II, but many statisticians will not be impressed. There are too many ways to analyze the same data, they say, some of which will inevitably come out positive. Peter Hobbs of the University of Washington has already done his own analysis of the reanalysis, using what he says are more suitable control stations. In his study, there is no significant seeding effect. Hobbs's analysis, which has been submitted for publication, will not be the last study of this 10-year-old experiment.

Even if the statistical questions can be resolved, the Climax experiments seem to have lost some of their strong physical rationale. Mielke believes that their method for inferring cloud-top temperatures in the absence of direct measurements does not have the physical basis once attributed to it. The inferred temperatures do seem to identify days on which seeding is particularly effective, he says, but cloud physicists cannot say why it works that way.

In light of such uncertainty, even among the better designed experiments of the past 30 years (see box), some researchers have been calling for a "return to basics" (*3*). Statistically convincing weather-modification experiments, they argue, will be difficult or impossible to design without a better understanding of the physical processes involved. Perhaps the best example of the back-to-basics movement is the Bureau of Reclamation's High Plains Cooperative Program (HIPLEX). Researchers conducted randomized seeding experiments during the summers of 1979 and 1980 in eastern Montana in order to verify their long-held assumptions about how seeding works. No one has found a major flaw in HIPLEX's experimental design.

Things went well with HIPLEX, up to a point. The object was to amass statistical evidence supporting each step of the precipitation process. Dry Ice seeding of small cumulus clouds did produce micrometer-size ice particles from the supercooled water droplets in the cloud. The ice particles grew during the first 8 minutes after seeding at the expense of the liquid water, but there is no statistical evidence that they reached the 2- to 3-millimeter size required in order that they fall as precipitation.

Then the unexpected happened—most of the clouds ran out of the liquid water essential for further ice particle growth, according to William Cooper of the University of Wyoming. Cooper blames the incorporation of dry air into the clouds, which evaporated the liquid water. In other words, these clouds died an early, natural death. Those clouds that did persist seemed to support particle growth to precipitation size, Cooper says, but there were too few such clouds to provide statistically significant results.

Cooper noted that HIPLEX researchers intentionally chose small clouds that would not produce much natural rain so that the effects of seeding would stand out. These clouds have shorter lifetimes, he says, but HIPLEX experimenters gambled on being able to pick out those that would persist and grow from those that would quickly evaporate. In spite of a much respected statistical design, HIPLEX ran afoul of the limited ability to understand and predict cloud behavior. Researchers are hopeful that analysis of the Cooperative Convective Precipitation Experiment (CCOPE), conducted at the same site during the summer of 1981, will improve the predictability of such cloud behavior.

Weather-modification researchers have learned some hard lessons, but tougher times may lie ahead. Between budget pressures and scientific retrenchment, weather modification experimentation in the United States may soon be at the lowest level in decades. President Reagan's 1983 budget virtually puts the National Oceanic and Atmospheric Administration (NOAA) out of weather modification research, although Congress may attempt to restore some of these funds. NOAA's FACE program has ended in a failure to confirm any seeding effect. Its Stormfury program, an ambitious attempt to reduce hurricane wind speeds, was falling victim to scientific problems before the budget ax ever fell (see box). The Bureau of Reclamation's HIPLEX program lost its funding after the 1980 season. The Bureau is able to continue its Sierra Cooperative Pilot Project, a 10-year effort to increase precipitation in the Lake Tahoe area of the Sierra Nevada. It is also proposing the 8-year Colorado River Enhanced Snowpact Test (CREST). Both are generally regarded as soundly designed programs with a good chance to resolve the questions about enhancing snowfall and rain.

The burden on these remaining programs will be great. "It's really a tragic thing," says Charles Hosler, a Pennsylvania State University meteorologist who has been working in the field since near its beginnings. "There's been so much waste, many, too many optimistic statements. Confidence in us has eroded all along. Now that we're getting our act together, there are these funding cuts."—RICHARD A. KERR

References

1. A. Gagin and J. Neumann, *J. Appl. Meteorol.* **20**, 1301 (1981).
2. P. Mielke *et al.*, *ibid.*, p. 643.
3. R. R. Braham, *Bull. Am. Meteorol. Soc.* **62**, 55 (1981).