Weather Modification: A Technology Coming of Age

Attempts to modify the weather have a long and controversial history. Because meteorological phenomena show large natural variations, it has often proved difficult to determine what effects, if any, are caused by human intervention. Cloud seeding techniques are the basis of most weather modification attempts, and they have been used both commercially and scientifically for 25 years. But even well-documented and randomized early experiments, such as the Whitetop trials carried out in Missouri from 1960 to 1964, produced ambiguous and disputed results. Despite past problems, there is now considerable optimism among meteorologists who are working on weather modification techniques. Increased understanding of the physics of cloud systems has brought weather modification to a new stage of development. One feature that distinguishes present efforts from most earlier attempts is the use of detailed mathematical models of the phenomena being modified to determine suitable conditions for seeding and to predict the resulting effects. The favorable results of a number of recent experiments indicate that operational programs may become feasible in the not-too-distant future.

Seeding techniques for all types of weather modification depend on the providing of nuclei on which condensation or freezing of the water vapor and supercooled moisture in the air can take place. Silver iodide is commonly used for this purpose because it readily forms large numbers of suitable particles—between 10^{10} and 10^{14} per gram—although lead iodide, Dry Ice, and even table salt have been used as well.

The effects of seeding on a particular cloud appear to depend dramatically on such details as cloud temperature, number of nuclei present, and where in the cloud nuclei are added, so that seeding at random is not especially likely to produce desired results. If the number of naturally occurring nuclei is sufficient to allow the freezing of much of the available supercooled water in a cloud, for example, the addition of more nuclei is thought to result, on the average, in smaller ice crystals; the smaller crystals melt and evaporate more rapidly on their way down so that less precipitation reaches the ground. Very strong storms with taller and colder clouds are often relatively efficient in releasing their moisture, so that it appears to be the warmer and more marginal cloud systems that offer the best chance for man-assisted increases in precipitation.

In addition to increasing or decreasing precipitation, nuclei from seeding can also influence the type of precipitation and electrical phenomena in the cloud, thus providing a basis for hopes of hail and lightning suppression.

A variety of methods are used to get the artificial nuclei into the cloud. For most applications flares containing silver iodide are ignited and dropped from a plane. Airborne ramjet generators that burn acetone with silver iodide have also been developed; these generators are capable of delivering large numbers of nuclei at the controlled rates necessary in some research applications. Ground-based generators, which have the advantage of lower cost but which must depend on the prevailing wind to transport the nuclei up into the clouds, are also used. Rockets and artillery shells have been used to deploy seeding material in hail-suppression programs in the Soviet Union.

The largest precipitation modification experiment to date in the United States is a pilot project, on the upper Colorado River basin, that is part of the Bureau of Reclamation's Project Skywater. The experiment consists of an attempt to increase the snowfall, and hence the runoff, in a 3300-square-mile area of the San Juan Mountains near Durango, Colorado. Seeding from 33 ground-based generators began this past winter. Precipitation is measured by a network of rain gauges, and runoff will be determined by monitoring stream flow. On the basis of earlier experiments conducted near Climax, Colorado, the Project Skywater director Archie Kahan expects the seeding to increase snowfall in the target area by an average of 16 percent. This would be equivalent to an additional 250,000 acre-feet (1 acre-foot = 0.123 hectare-meter) of water for the Colorado River system.

Not all of the snow clouds that are formed by condensation of water vapor as a mass of air moves upward to pass over the mountain range are selected for seeding. According to a numerical model of orographic clouds, as mountain produced clouds are called, seeding would tend to increase precipitation when the temperature of the cloud tops is between −25°C and −12°C and decrease the snowfall when the temperature is outside these limits. The model, which was developed and tested by a group headed by Lewis Grant at Colorado State University in Fort Collins, determines the optimum concentrations of ice nuclei as a function of cloud temperature. Hence the possibility exists that in severe winters seeding could be used to reduce the snowfall. For the present, however, seeding is attempted only on days in which the temperature at 500 millibars—the approximate height of cloud tops in the San Juan region—lies between −12°C and −25°C. Of the suitable days, only about half are seeded following a randomized series of instructions in accordance with the statistical design of the experiment.

The need for water in many of the western states is urgent. However, not everyone agrees that more snowfall is highly desirable. Residents of Ouray, Colorado, have objected strongly to the seeding program on the basis that additional snowfall might increase the number or severity of avalanches, which are already frequent in the area. Because of this local resistance, seeding is for the present restricted to the uninhabited half of the target area while research on avalanche causes and prediction methods is undertaken. But the incident is typical of the kinds of conflicting opinions about the weather that arise wherever modification attempts are made. Another common concern is that successful seeding in one region would cause decreased precipitation in downwind areas. There is apparently no well-documented evidence that any large effect occurs; many meteorologists believe that downwind effects, whether positive or negative, depend greatly on the local situation. On the average only about 10 percent of the moisture in the air falls naturally as rain or snow, and a seeding program such as the San Juan experiment removes only an additional 1 to 2 percent.

Because the San Juan project may lead rapidly into an operational program, it is being studied unusually carefully. A preliminary survey showed no signs of short-term ecological effects, since the additional snowfall expected is well within the range of the natural variation of the region's precipitation. Scientists from several Colorado universities are undertaking a detailed 4-year study of the long-range impact of the seeding on plants, animals, and climatic change. Simultaneously a technology assessment study of the economic consequences for the region of an operational seeding program is being undertaken with support from the National Science Foundation (NSF).

A different weather modification technique under development by the National Oceanic and Atmospheric Agency (NOAA) laboratories in Florida is aimed at increasing rainfall from tropical cumulus clouds. Massive seeding is used to increase the buoyancy forces in an individual cloud by warming the cloud air with the latent heat that is released when supercooled cloud water freezes. In cumulus clouds buoyancy forces control the cloud's rate of growth, so that seeding may cause the cloud to grow higher and more rapidly than it otherwise would; in contrast, the rate of growth of orographic clouds is usually controlled by larger circulation patterns, so that seeding does not appreciably affect the overall flow field. The basis of the rainmaking method is that larger clouds, because of their increased size and lifetime, usually rain more than do small ones. Seeding is done with silver iodide flares which are dropped directly into suitable clouds from airplanes. Rainfall is measured with a radar that has been calibrated by comparison with precipitation gauges on the ground.

The results of a series of experiments by the NOAA scientists, headed by Joanne Simpson, indicate that seeded clouds yield on the average more than three times as much rain as unseeded clouds [*Science* **172**, 117–125 (1971)]. The seeding technique is most successful on fair days; on rainly days, seeding seems to be ineffective or to have the effect of slightly decreasing rainfall, presumably because the rainy-day clouds naturally grow larger and are correspondingly more efficient in releasing rain. A computer model has been developed that can predict the growth and rainfall to be expected from cumulus clouds under various atmospheric conditions. In particular, the model can predict the amount of additional growth and rainfall that would result from seeding a cloud.

Although the seeding of individual clouds seems to be a proven technique, it yields only 100 to 250 acre-feet of additional water per cloud. In contrast, when two single clouds merge, they can release more than 30 times as much water as a single cloud, according to Simpson. Hence the possibility of promoting mergers and other multicloud systems by seeding adjacent clouds appears to offer the best hope for large-scale rainmaking. But whether the model and seeding techniques developed for the semitropical conditions of southern Florida will be applicable to cumulus clouds in other parts of the country is still unknown.

Buffalo and other cities on the downwind edge of the Great Lakes are often hampered by heavy snowfall from "lake-effect" storms that pick up moisture from the lake and deposit as much as 100 inches (2.5 m) of snow a year in a narrow band along the shoreline. As a mass of air flows off the lake, it encounters an increased frictional drag over land which combines with heat from cities to force the air upward as if over a mountain. The cities are also sources of pollutants that serve as artificial nuclei which contribute to the intense local snowfall. Preliminary studies indicate that massive seeding of the storms might help redistribute the same amount of snowfall over a wider area; the hypothesis is that large numbers of nuclei will cause the formation of more, and hence lighter, snow crystals that will drift farther inland. A group of meteorologists, headed by Helmut Weichmann, from a NOAA laboratory in Boulder, Colorado, have been testing a variety of seeding materials and methods and hope to begin seeding experiments on actual storms this coming winter. A numerical model of lake-effect storms in the Lake Erie region, which was developed by Ronald Lavoie of Pennsylvania State University and others, is being used to predict cloud heights and snowfall rates. Although the primary experimental goal of the program is snowfall redistribution, preliminary results indicate that—as in the case of the San Juan experiment—the process could be turned around by seeding warmer clouds to increase snowfall far out on the lake and hence increase water levels in the lake.

One of the more exotic possibilities of weather modification is the suppression of cloud-to-ground lightning, which every year starts large numbers of forest fires. Apparently lightning from small, dry storms is most frequently responsible, since larger storms often put out their own fires. Although electrical processes in a cloud are poorly understood at present, one hypothesis holds that electrical charges are built up by the interaction of liquid and solid particles. Hence by overseeding a cloud to convert all of its supercooled water into ice, the microphysical balance is changed in a way that is thought to favor shorter and less frequent lightning discharges. A small group of scientists, headed by Donald Fuquay of the U.S. Forest Service laboratory in Missoula, Montana, are modifying existing cloud models to include electrical effects and designing field experiments. The research is still in its preliminary stages, but very limited tests several years ago give some basis for encouragement.

A large hail research project funded by NSF is scheduled to begin exploratory seeding experiments in Colorado in the summer of 1972. No models of hailstone growth are available at present, but efforts to develop them are under way. Modeling work is also proceeding on hurricanes as part of NOAA's Stormfury Project, and three storms have been seeded in past years in an attempt to see whether their destructive wind velocities can be reduced. Other efforts are aimed at dispersing fog.

Although seeding techniques are still experimental, in several cases they have been applied in near-emergency situations. At the request of farmers, NOAA scientists in Florida are currently seeding clouds in an attempt to alleviate a severe drought [*Science* **172**, 40 (1971)], and during the forest-fire season the Forest Service has seeded in high-risk areas of the northwest in response to local pleas for help. As seeding techniques continue to improve, it is likely that they will be increasingly called upon. But the operational use of weather modification techniques on a large scale raises difficult questions about legal responsibilities, conflicting social desires, and appropriate governmental regulatory activities. At the current rate of progress, the remaining scientific problems involved in this new technology will undoubtedly be resolved before the legal and political mechanisms to oversee its use are established.

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