CLOUD SEEDING AND RAINMAKING

Louis J. Battan *University of Arizona*

UNLESS NEW sources of fresh water are found, the world will face serious hardships in the years to come. This is particularly true in the U.S., where the daily bath, the sprinkled lawn and the air-conditioned office have become necessities rather than the luxuries they used to be.

An examination of rainfall and snowfall measurements, going back as far as the records extend, shows wet periods and dry periods, some long, some short. As long as there were few people with small thirsts, there was plenty of water even during dry spells. But the population curve does not rise and fall as does the precipitation curve. The number of people has followed a steady upwards trend and it continues to increase.

We are at that point where several dry years in a row cause great discomfort and concern. This was certainly the case in the northeastern U.S. in the mid-sixties. Fortunately, in the late sixties, wet weather returned and the immediate crisis passed.

Unfortunately, the population continues its relentless climb and each man's use of fresh water does likewise. The next drought will be much more painful to man than the last one, and the one after that still worse. No one can tell when the droughts will come, but you can be absolutely sure they will occur.

What is the solution to this dilemma? It would take very drastic measures to reduce per capita water consumption; therefore, we must find more fresh water. Desalinization of ocean water is a distinct possibility and great efforts are being made in many places to find economical means of removing the salt. Also, progress is being made in the reclamation of sewage water.

The principal source of fresh water today is the atmosphere. On the average, about 40 inches of water falls over the earth every year, but more than half of it lands in the oceans. If we could find an effective way to increase precipitation over the continents, many of our water problems would be reduced greatly. In recent years, meteorologists have begun to feel optimistic about the possibility of attaining such a goal. This essay discusses some statistical aspects of such a search.

FORMATION OF PRECIPITATION

Much of the precipitation reaching the ground originates in the form of ice crystals. On cold days in the winter, the clumping of crystals produces snowflakes that fall to the earth. At other times, when the air is warm, the snow particles melt as they fall and they reach the ground as rain.

Not all rain is formed this way. Some rain develops as small cloud droplets that collide, merge, and grow large enough to fall to the surface of the earth. In this brief essay, it will not be possible to examine this second process any further. We shall concentrate on the precipitation mechanisms involving ice particles because most investigations aimed at rainfall stimulation try to take advantage of the "ice-crystal process."

ICE-CRYSTAL PROCESS

Clouds form as a result of the condensation of water on tiny solid particles in the atmosphere, known as condensation nuclei. They come from blowing soil, swirling smoke, and sea spray. A typical cloud is composed of water droplets ranging in diameter from perhaps 5 to 50 microns. A human hair is about 10 microns in diameter, so it is evident that the droplets are very small, much smaller than typical raindrops, which may have a diameter of 2000 microns (2 mm.).

Water clouds often form in regions where temperatures are below 32°F and still remain in the liquid state. Such clouds are called *supercooled*. The failure of the drops to freeze is attributed to the purity of the water. In extreme cases the clouds can be supercooled to temperatures below —30°F.

Clouds composed of small water droplets, whether supercooled or not, normally cannot produce rain or snow unless some mechanism other than condensation enters the process. The first sound theory for the formation of precipitation was offered in 1933 by the Swedish meteorologist, Tor Bergeron, who theorized that when tiny ice crystals are introduced into a supercooled cloud, precipitation could develop. Because of the difference in the physical properties of water and ice, the ice crystals grow rapidly and the water droplets evaporate. As the crystals enlarge they start falling through the cloud and grow even faster as they collide with other crystals and supercooled droplets. In this way a snowstorm may be produced.

CLOUD SEEDING

In 1946, Vincent J. Schaefer at the General Electric Laboratories at Schenectady, New York, was studying supercooled clouds in a laboratory cold chamber. He discovered that when chips of Dry Ice fell into such a cloud, large numbers of ice crystals formed, grew, and fell to the bottom of the chamber. This was the first clear demonstration of the theory advanced by Bergeron more than a decade earlier.

Schaefer and his colleagues also carried out experiments in the atmosphere. They flew over the tops of thin layers of supercooled clouds (called *stratus clouds*) and dropped Dry Ice pellets from an airplane. In a matter of minutes, the cloud structure in the regions seeded with Dry Ice changed. Ice crystals grew and fell as the water droplets evaporated, leaving a "hole" in the cloud through which the ground could be seen. As the airplane flew below the cloud, light showers of ice crystals and snowflakes were observed to be falling.

This experiment has been repeated in many places by many people. In certain tests, an airplane was flown along prescribed patterns over a uniform cloud deck and seeded along the way. The pattern of cloud dissipation corresponded to the seeding pattern. One of the more spectacular had a shape like a racetrack cut right out of the cloud.

Incidentally, one of Schaefer's colleagues, Bernard Vonnegut, discovered that tiny particles of the chemical silver iodide also are effective ice nuclei. For many cloud-modification operations, silver iodide is more convenient to use than Dry Ice.

Today supercooled fogs and low clouds over certain airports in the U.S. and abroad are cleared on a regular basis by means of cloud-seeding techniques. These operations have allowed airplane movements which would not have been possible if the clouds had not been modified.

RAINMAKING

As noted earlier, when thin, supercooled decks of stratus clouds were dissipated by means of Dry Ice seeding, light snow showers occurred under the seeded regions. Some meteorologists believed that the precipitation was light because the clouds were shallow. It was argued that if thicker clouds were seeded, greater quantities of precipitation could be caused to fall. Skeptics responded that in the case of thick clouds, nature would supply the necessary nuclei and the addition of artificial nuclei would have no effect.

If enough were known about the physical and chemical nature of clouds and precipitations, calculations could be made of how much precipitation would occur with and without seeding. Unfortunately, we do not have the detailed knowledge required for precise calculations of this kind.

The only satisfactory way to ascertain if cloud seeding can increase precipitation has been by means of experiments in the atmosphere. The major difficulties faced by scientists engaged in testing the effectiveness of a seeding technique has been the great variability of precipitation in time and space and the inability to make accurate forecasts of precipitation.

Figure 1 shows curves of the August rainfall in Tucson, Arizona, and in New York City for a 39-year period. The dashed lines show the average rainfalls at the two cities. The variations from year to year and decade to decade are obvious. It is evident that August rainfall in New York was substantially below the average during the drought period 1963–66.

In some of the early attempts at rainmaking, very crude schemes were used to evaluate the effects of seeding. One of them involved the comparison of rainfall during a seeded or several seeded periods with rainfall over the same area during earlier unseeded periods. In one such test, rainfall during one seeded season exceeded the mean rainfall by 15%, and it was reported that seeding probably had increased the precipitation. The data in Figure 1 show why such a conclusion is questionable. It is evident that mean rainfall occurs very infrequently. Instead, the actual monthly amounts deviate greatly above and below the mean. Herbert C. S. Thom, a well-known climatologist, has indicated that if you wish to test the hypothesis that seeding does not increase rainfall and you do this by comparing the rainfall over a target area with historical data, extremely large seeding effects would have to occur in order to be detected. As a matter of fact, with typical rainfall distributions, seeding would have to cause about three times the median precipitaton in order to give a high probability of rejecting the no-increase hypothesis.

In view of the fact that, in 1972, even those convinced of the effects of seeding talk about possible precipitation increases or decreases ranging from about 5 to 50%, it is clear that it is unlikely that seeding effects can be identified simply by examining the rainfall in a target area. In order to detect seeding effects amounting to about 10% and to do it in a reasonable

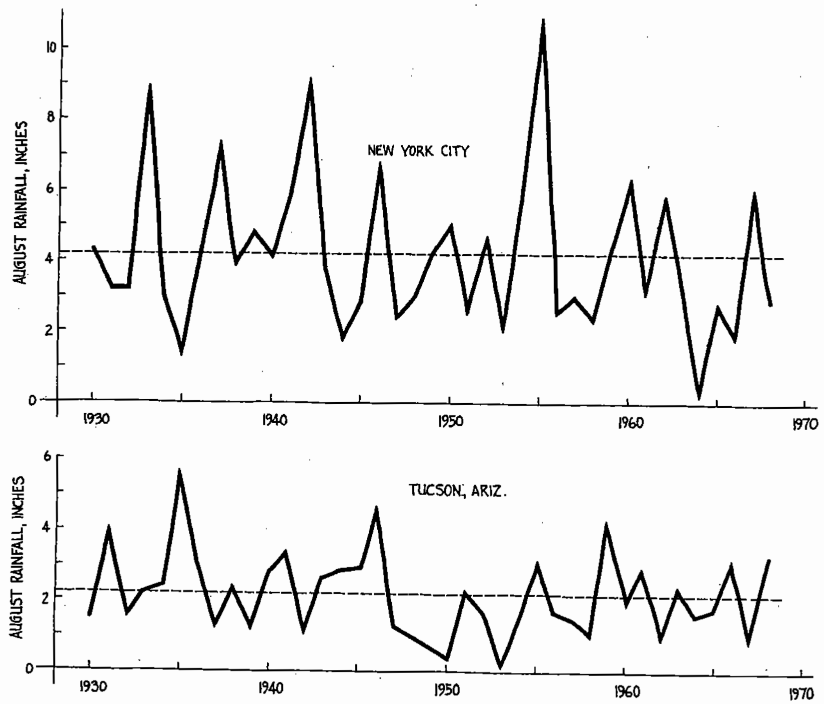

FIGURE 1

Inches of August rainfall in Tucson, Arizona, and New York City, 1930–68. Sources: Institute of Atmospheric Physics, University of Arizona, Tucson. World Weather Records, *U.S. Department of Commerce (1930–60).* Climatological Data: National Summary, *U.S. Department of Commerce (1961–69)*

length of time, it is necessary to use a scheme for estimating how much precipitation would have fallen on the target area if there had been no seeding. This has brought statistical regression methods into the picture.

REGRESSION METHODS

The character of the weather often is uniform over distances exceeding several hundred miles. Weather maps show large regions of warm air separated

by so-called "fronts" from large regions of cooler air. Within each air mass there are somewhat distinctive atmospheric conditions, clouds, and precipitation. Hence, the average precipitation of two areas some tens of miles in diameter and close to one another are correlated. If care is taken to select areas having similar physical geography and if monthly rainfalls are examined, correlation coefficients exceeding 0.9 are sometimes found. (Correlation coefficients measure similarity between two series; a value of 1 is the highest possible positive value, 0 is low, and −1 means the two series move in exactly opposite directions such as 1, 2, 3 versus 6, 4, 2. See the essay by Whitney for a further explanation of correlation.) This fact has made it possible to obtain results showing that cloud seeding may influence precipitation.

In general the regression methods take into account two areas: a target area and a control area. On the basis of past historical data, a scatter diagram is drawn and a regression line is established as shown in Figure 2. In this illustration the quantities plotted on each axis are not the actual precipitation amounts, but rather the square root of the precipitation. This is called the *transformed precipitation* and is used to give the scatter of the points around the regression line a more symmetrical shape.

It is not necessary to concern ourselves with the details of this analysis. The important point is the following. Having established a regression line such as that in Figure 2, we can, by measuring the precipitation in the control area, estimate the range of rainfall quantities expected over the target area. This knowledge, in turn, makes it possible to estimate the likelihood of the occurrence of results as extreme as those observed during a seeded period (or periods) even if seeding has no effect. For example, the cross in Figure 2 might represent the precipitation amounts measured in the target and control areas during a seeded month. Various statistical techniques exist for calculating the probability that, given the rainfall measured in the control area, the rainfall in the target area occurred by chance.

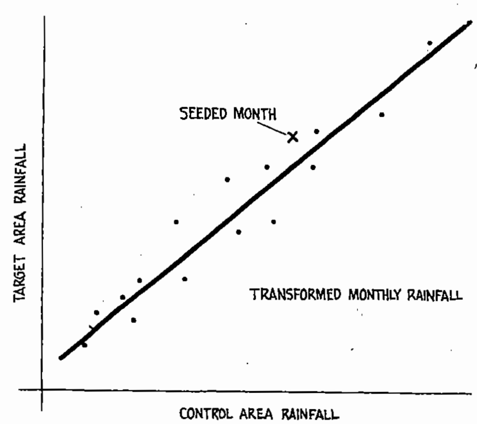

FIGURE 2

Comparison of rainfall in the control area and the target area, plotting square root of rainfall in inches. The dots refer to unseeded months and the cross to a seeded month for the target area. The departure of the cross from the line is similar in size to the departures for the unseeded months

The regression method appears to be sufficiently straightforward, but several pitfalls must be avoided if the conclusions from such an analysis are to be widely accepted. First of all, it is necessary that there be adequate controls over the selection of the seeding periods. An effective way to do this is to use a suitable randomization scheme in deciding when to seed.

Still another danger is the possibility that the historical regression might change significantly from one period to another. For example, would a regression line for the years 1930–50 be the same as the one from 1950–70, or would it be better to use a 40-year regression line? At this time, it is not possible to give a general answer to this question.

CROSSOVER EXPERIMENTS

Researchers in several countries have tested the efficacy of cloud seeding by means of a technique known as the *crossover design*. As in the target-control method discussed above, two areas are involved, but in the crossover design either one of the areas may be seeded, the decision being made according to a suitable randomization scheme.

The higher the correlation between the precipitation in the two test areas, the more efficient is the crossover design in determining whether cloud seeding has increased or decreased the precipitation. If seeding is effective, crossover experiments will detect the effect after fewer tests than would be required if the target-control design were used. The crossover procedure has been employed successfully in Australia where it originated, in Israel, and in the U.S.

SOME RESULTS

Many rainfall modification projects involving randomization have been conducted in various parts of the world. Some of them are still in progress. The results are mixed. In some projects, more precipitation occurred during the seeded periods. For example, experiments conducted near Lake Almanor, California, during the period 1962–67 showed that with cold temperatures and west winds, cloud seeding apparently increased precipitation by an average of 37 percent (Mooney and Lunn 1969). In other tests, such as those conducted by the University of Chicago, in central Missouri between 1960 and 1965, cloud seeding apparently decreased rainfall (Braham and Flueck 1970). In still other programs, it appears that cloud seeding had no effect.

The results of the field tests show convincingly that sometimes cloud seeding influences the quantity of rain or snow reaching the ground. The chances of increasing precipitation from winter clouds over mountainous regions appear to be greater than are the chances of getting more rain from summer showers and thunderstorms, but such a generalization must be treated with caution.

Recent research indicates that by means of ice-nuclei seeding, individual summer clouds having certain specific characteristics were caused to produce more rainfall than they would have produced if they had not been seeded. On the other hand, such special clouds may not contribute substantial fractions of total summer rainfall. For example, scientists in the Soviet Union have reported that rainfall from certain types of summer clouds has been more than doubled by cloud seeding. They also have indicated, however, that such clouds account for no more than one percent of the total summer rainfall.

SUMMARY

The great variability of precipitation and our inability to make accurate quantitative predictions of rainfall have made it necessary to conduct experimental programs in order to establish whether or not particular cloud-seeding techniques can increase precipitation. It has been found that seeding with ice nuclei, that is, Dry Ice or silver iodide particles, may influence precipitation in some cloud systems. We still have not learned how to identify those systems where precipitation can be increased reliably.

Many atmospheric scientists are convinced that it should be possible to increase precipitation by economically significant amounts and hence to help quench the water needs of an increasingly enlarging and thirsty population. An expanded program of carefully designed and executed field experiments is needed to test existing ideas and hopefully generate new ones.

REFERENCES

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