

CLOUD SEEDING: KEEPING OUR FINGERS CROSSED

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Abstract

Supporters of cloud seeding to augment precipitation speak of the stages of weather modification from an art to a science. Critics suggest that cloud seeding remains more of an art than a science, and that claims of successful precipitation augmentation lack scientific documentation. Most recently, the Committee on Weather Modification, Irrigation and Drainage Division of the American Society of Civil Engineers (ASCE), prepared guidelines for "water resource managers who might become involved in the decision-making process for implementing a weather modification project." The guidelines suggest that cloud seeding to augment precipitation is an accomplished fact. There are no references to the unanswered questions that have been raised in cloud seeding experiments such as indications of negative downwind effects. The water resource manager could be handicapped in making his decision without an adequate background on weather modification experiments. This paper is suggested as a supplement to the guideline prepared by the Committee on Weather Modification. The unwary water resource manager should have access to, or be aware of, the uncertainties that remain in cloud seeding. At the very least, he should know that there is a considerable bibliography available that suggests cloud seeding to augment precipitation is not an accomplished fact.

Introduction

Commercial cloud seeding, to augment precipitation, has become popular in the last 30 yrs. Cloud seeding experiments and evaluations of commercial cloud-seeding operations were concentrated in a 20-yr period from the mid 1950's to the mid 1970's, and out of these experiments and evaluations has come a large bibliography describing these projects and efforts to analyze them. On the one hand, commercial cloud-seeding projects generally did not lend themselves to statistical analysis. On the other hand, analyses based on experimental design have not verified increases in precipitation from cloud seeding. In fact, many have suggested decreases, as well as increases, although the decreases or increases were usually not statistically significant. After-the-fact evaluations of cloud seeding experiments have been popular because of the expensive alternative of carrying out new experiments. These after-the-fact evaluations generally rely on partitioning the data that have been collected, and have provided a mixed bag of conclusions suggesting either increases or decreases. Often, it has come down to deciding whom you believe, and this dilemma suggested the title for this paper.

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Scientific Background

The birth of commercial cloud seeding to augment precipitation probably goes back to the early work of Langmuir, Schafer, and Vonnegut in the 1940's. They carried out laboratory studies on various materials which could serve as nuclei or agents in converting super-cooled water droplets into ice crystals (19, 23). In theory, if the super-cooled water droplets could be converted to ice crystals more rapidly than normal, there would be additional precipitation, as well as added energy from the latent heat of fusion, which would invigorate cloud growth.

Vonnegut found that two of the better freezing nuclei were silver and lead iodide (23), but dry ice was used most often in the early cloud seeding efforts. However, with the development of nuclei generators, silver iodide soon became the principal cloud seeding agent (7). Two principal methods evolved for cloud seeding -- by generators in aircraft and by ground-based generators. Seeding by aircraft was considered more effective, particularly for summer rainfall, while seeding with land-based generators was cheaper and more practical for winter storms. In both methods, the operator assumes that the generated nuclei are distributed within the cloud system and serve to accelerate the precipitation process. The natural availability of nuclei, including small ice crystals, the relative cloud temperatures, and available moisture combine to add to the uncertainty of actual results.

Two publications of particular significance in weather modification are the National Academy of Science (NAS) reports on "Weather and Climate Modification: Problems and Prospects" (1966), and "Problems and Progress" (1973) (13, 14). These publications provide a thorough and objective review of planned weather modification through 1971. Both publications have complete and accurate references from which the interested person can expand his knowledge of weather modification. Both reports were cautiously worded and admitted mixed results in analyses of cloud seeding experiments and programs. Both publications suggested better odds in seeding of winter storms than in seeding summer convective storms. A third NAS publication on climatic fluctuations and agricultural production (15) contains a chapter on weather modification with references through 1975. Of particular interest in this publication is the initial report on results of the San Juan Project in southwestern Colorado. The results, based on the project design, did not indicate an increase in precipitation from cloud seeding (4). Later analyses, after the data were ranked and partitioned into groups determined from observations, claimed more positive results for certain groups (but not for others), (5).

Planned Modifications

From the very beginning, cloud seeding experiments have been launched with great optimism and promise of positive results. These promises and optimism have handicapped efforts to evaluate weather modification on an objective basis. There has been a built-in desire to succeed in most major experiments. Conclusions were mostly "cautiously optimistic," although from the results, they often could have been quite pessimistic. When unbiased results have not given the desired answers, there has been

a tendency to reevaluate experiments to obtain more positive conclusions. In some cases, only the more positive aspects of the experimental results appear in the summary.

Winter Cloud Seeding

The USBR carried out the ambitious Colorado Basin Pilot Project, in the San Juan Mountains of southwest Colorado (the San Juan Project), from the winter of 1970-1971 through the winter of 1974-1975. The primary objective of this study was to determine if seeding of winter clouds, to increase precipitation and subsequent runoff in the Colorado River, would be economically feasible. The project was to apply the most up-to-date knowledge in cloud seeding to a feasibility study (as opposed to an experiment, as in the past). The project included several secondary aspects such as possible social and legal problems of cloud seeding which tended, if anything, to distract from the basic question of scientific feasibility. The project is of particular interest in the Southwest, because the lower Colorado River Basin is a water-short area, and augmenting water supplies by cloud seeding has been suggested as a partial solution to the water problem.

The San Juan Project was designed to prove theories that evolved from several smaller scale projects and experiments, particularly the Climax (Colorado) experiments (4, 8, 9, 10, 11, and 12). The initial results, published in 1975, did not show an increase in precipitation attributable to cloud seeding (4). In fact, the data indicated about a 10% decrease in precipitation from cloud seeding. The comprehensive 664-page report, which was released the following year (5), stressed all the problems with the project -- inadequate experimental design, spatial and temporal precipitation variability, the limited gauging network, and so on. Also described was an after-the-fact evaluation based on ranking and partitioning data which suggested that, if seeding had occurred only on certain days, there would have been an increase in precipitation. The report concluded that seeding on all the days that were forecasted as favorable had a negative effect on precipitation on some of those days. However, the most up-to-date forecasting techniques were used based on the latest theoretical and experimental input. The 20-page executive summary did not report the negative aspects of the study, but concluded that the study had shown potential for an average increase of 10% in winter precipitation, which would result in a 19% increase in runoff (160,000 acre-feet) from the San Juan Mountains. If extrapolated to other mountainous areas in the Colorado Basin, this would mean an increase of over 2,000,000 acre-feet in the Colorado River. It is these figures which are so often quoted to support operational winter cloud seeding in the Colorado River Basin.

There are several weaknesses in the conclusions, and there are dangers in accepting the conclusions without reservation (reasons for keeping our fingers crossed). As was stated, the cloud seeding which was carried out during the winter seasons of 1970-71 through 1974-75 did not increase precipitation. After-the-fact evaluations suggested that if the seeding had been done differently, there would have been a precipitation increase. However, no further pilot projects have been attempted to prove or disprove these conclusions, and there is no evidence that

the required conditions for "positive" seeding could be forecast in advance, an obvious requirement if the hypothesized favorable conditions are indeed favorable.

Another potential problem is the attitude of the public, including public officials. If the public perceives that cloud seeding will increase water supplies in the Colorado River Basin by 19% (or possibly even more in the public mind), plans will be made to use that water. If the increases are not forthcoming, a water-short region could become a region with a critical water supply problem.

Convective Cloud Seeding

There have been several significant efforts to seed summer thunderstorms to increase rainfall (13, 14). Two experiments, carried out in the midwestern and western United States (1, 2, 3, 6, and 16), did not answer the uncertainties in convective cloud seeding, and did, in fact, suggest negative, rather than positive, effects in both target and far downwind areas. Experiments carried out in Florida have suggested some successes tempered with many unexplained anomalies and uncertainties (20, 21). Some of the uncertainties involved in convective cloud seeding occur because of the extreme rainfall variability, the difficulty in gauging rainfall over an area, and the difficulty in predicting what will happen without seeding.

The most comprehensive convective seeding experiments in the Southwest were carried out by the Institute of Atmospheric Sciences, University of Arizona, in the summers of 1957 through 1960 (1) and 1962, 63, and 64 (2). Silver iodide generators, mounted in aircraft, were used to seed clouds over the Santa Catalina Mountains. The seeding was for randomized pairs of days on a seed-no seed and no seed-seed basis for periods of at least 2 days of predicted rainfall. Seeding began at about noon, upwind from the mountains, and continued for up to 4 hours. Analyses of the data collected in the first 4 yrs (1957-1960) indicated a statistically non-significant decrease of 30% in seeded rainfall. The experimental design was revised with changes in identifying seedable days and seeding procedures, and the experiment was repeated in the summers of 1962, 63, and 64. Again, the results were a statistically non-significant 30% decrease in seeded rainfall. The conclusions for both experiments was that the negative results could have been by chance (2). A second suggested explanation was that the clouds were "overseeded," which caused the decrease. A reevaluation of the Arizona experiments, assuming that the two experiments were similar enough to evaluate as one, indicated a statistically significant decrease in seeded rainfall (16). At the very least, and seen in the most objective manner, no significant rainfall increases have been suggested. If there were results, they were probably negative.

Downwind Effects

Possible downwind effects of cloud seeding projects have worried many investigators (11, 16, 17, 18). Apparent downwind seeding effects, generally negative, have been reported for both winter and summer cloud seeding. For example, there was an indication of negative downwind

effects in the Jemez Mountains, New Mexico, winter cloud seeding experiment (11). However, most winter cloud seeding experiments, such as those in the Sierra Nevadas of California and the San Juan and Rocky Mountains of Colorado, do not lend themselves to analysis, since the areas immediately downwind are generally in so-called "shadow" areas, which are much drier and more unpredictable than the mountainous target areas.

The most significant indication of downwind negative cloud seeding effects came from the evaluation of rainfall records on the USDA Walnut Gulch Experimental Watershed in southeastern Arizona for the period in which cloud seeding experiments were carried out by the University of Arizona over the Santa Catalina Mountains (17). Walnut Gulch is about 65 miles southeast of the Santa Catalina Mountains. Analysis of rainfall data from noon of the experimental days until noon of the following day indicated a significant decrease in rainfall on seeded, as opposed to unseeded, days. When the data were divided into days in which Walnut Gulch was "downwind" from the Catalinas, the decrease in seeded rainfall was highly significant (17).

Economics

Cloud seeding can have at least two possible effects: (1) to alter the probability that precipitation will occur, and (2) to alter the amount that does occur. Alter can mean to increase or decrease. Furthermore, the second possibility is more probable than the first, although the seasonal distribution is often more crucial than the total amount of precipitation. For example, the farmer may not want more rain during planting, but that may be when cloud seeding conditions are most favorable. At other times, say during the critical growth period for his crop, he may need rain, but there are no cloud seeding opportunities. Most economic evaluations assume that increases in annual and seasonal precipitation occur when needed and are beneficial. In reality, the times when rainfall is most needed are often times with the least chance of successful cloud seeding.

Conclusions

Conclusions reached by the weather modification panel in the 1973 NAS reports are still pertinent (14).

"There is increasing, but still somewhat ambiguous, statistical evidence that precipitation from some types of cloud and storm systems can be modestly increased or redistributed by seeding techniques. The panel now concludes, on the basis of statistical analysis of well-designed field experiments, that ice-nuclei seeding can sometimes lead to more precipitation, can sometimes lead to less precipitation, and, at other times, the nuclei have no effect, depending on the meteorological conditions . . ." (p. 3).

The panel also concluded that "in the longest randomized cloud-seeding research project in the United States involving cold orographic winter clouds (Climax), it has been demonstrated that precipitation can be increased by substantial amounts on a determinate basis," (p. 5).

Unfortunately, the San Juan Project, which was based on knowledge gained in the Climax experiments, did not validate the panel conclusion. The San Juan results were not available when the panel published their conclusions.

In the area of summer cloud seeding, the 1973 panel concluded that "the recent demonstration of both positive and negative treatment effects from seeding convective clouds emphasizes the complexity of the processes involved . . ." (p. 7).

The 1976 NAS Panel report (15) included a statement that "randomized experiments on convective clouds . . . in several states . . . were inconclusive, but strongly suggested a reduction in precipitation . . ." (p. 140). The 1976 panel also stated that "understanding the processes and developing the technology for augmenting precipitation from convective clouds is important from an agricultural standpoint. Experimental results encourage the hope that a useable technology may be possible, although current capability has not been established (p. 141)."

No data, or research results, or reevaluation of old projects have changed these conclusions on convective cloud seeding.

More recently, the American Society of Civil Engineers (ASCE) Weather Modification Committee authored guidelines for cloud seeding to augment precipitation (22) which are deceptively matter-of-fact. The only reference to possible uncertainties is a line by L. O. Grant, of Colorado State University, in the section on scientific basis: "despite these limitations, there is a good scientific and experimental basis for optimism that a sound cloud seeding technology can be developed for augmenting water supplies by at least small, but significant, amounts on certain occasions." (Emphasis is author's). Everything else in the guidelines suggests that cloud seeding is an accomplished fact, and that all one needs to do is to follow the guidelines to successfully increase precipitation.

Unfortunately, there has been very little, if any, advance in the science of cloud seeding since the 1960's and early 1970's, and the experiments of that period did not indicate that cloud seeding, to augment precipitation, was a proven reality. Many of the unstated assumptions in the guidelines may be true, but no one can be sure.

Summary

From the mid 1940's through the mid 1970's, there were numerous laboratory and field experiments on cloud seeding to augment precipitation. During the same period, a methodology evolved for commercial cloud seeding. By now, the scientific evidence has been so interwoven and obscured by conflicting experimental data and commercial cloud-seeding methodology that it is difficult to recognize one from the other. The most recent efforts to standardize the field of cloud seeding have some merit, but these efforts should not be confused with the scientific evidence on cloud seeding.

The scientific basis for determining, "a priori," the influence of

cloud seeding has not been established within the scientific community (13, 14, 15), and statistically significant experimental data are ambiguous, or even negative in some cases. Therefore, it would seem prudent to view cloud seeding to augment precipitation as a testable hypothesis rather than a proven or scientifically accepted technology. As stated earlier, caution in this particular instance, and with particular respect to water-short areas, may be in the public interest. Users should be aware of both the potential payoffs and the uncertainties, including possible decreases in precipitation, involved in cloud seeding to augment precipitation.

Appendix—References

1. Battan, L. J., and Kasander, A. R. 1960. Design of a program of randomized seeding of orographic cumuli. *J. Meteorology* 17:583-590.
2. Battan, L. J., and Kassander, A. R. 1960. Summary of results of a randomized cloud seeding project in Arizona. *Proc. Fifth Berkeley Symposium on Mathematical Statistics and Probability, Vol. 5, University of California Press, 29-33.*
3. Braham, R. R. 1966. Project whitetop -- A convective cloud randomized seeding project. The University of Chicago press.
4. Elliott, R. D., Court, A., Shaffer, R. W., and Hannaford, J. F. 1975. Colorado River Basin Pilot Project -- Third Interim Progress Report. Prepared for USBR, Report No. 75-1, Aerometric Research Inc., Goleta, California, 412 p.
5. Elliott, R. D., Shaffer, R. W., Court, A., and Hannaford, J. F. 1976. Colorado River Basin Pilot Project -- Comprehensive Evaluation Report. Prepared for USBR, Report No. AR1-76-1, Aerometric Research Inc., Goleta, California, 664 p.
6. Flueck, J. A. 1968. A statistical analysis of project whitetop precipitation data. *Proc. First Nat'l. Conference on Weather Modification (Albany, NY, April, 1968). Am. Meteorol. Soc., 26-35.*
7. Fukuta, N., Plooster, M. N., Armstrong, J. A., Gorere, A., Butz, J. R., Schaller, R. C., and Glen, L. 1977. The development of organic ice nuclei generators for weather modification; final report. Denver Research Inst. report to the National Science Foundation, 2 vol.
8. Grant, L. O., and Mielke, P. W. 1967. A randomized cloud seeding experiment at Climax, Colorado, 1960-1965. *Proc. Fifth Berkeley Symposium of Mathematic Statistics and Probability, Vol. 5, University of California Press, 115-132.*
9. Grant, L. O., Chappell, C. F., and Mielke, P. W. 1968. The recognition of cloud seeding opportunity. *Proc. First Nat'l. Conf. on Weather Modification (Albany, NY), Am. Meteorol. Soc., 372-385.*

10. Grant, L. O., Chappell, C. F., and Mielke, R. W. 1971. The Climax experiment for seeding cold orographic clouds. Proc. Int'l. Conf. on Weather Modification, Canberra, Australia, pp. 78-84.
11. Keyes, C. G., Stover, F. D., Lunsford, J. V., and Lentmer, M. 1973. Jemez Atmospheric Water Resources Research Project. Prepared for USBR, Contract No. 14-06-D-6803, New Mexico State University, Las Cruces, NM, 130 p.
12. Mooney, M. C., and Lunn, G. W. 1969. The area of maximum effect resulting from the Lake Almanor randomized cloud seeding experiment. J. Appl. Meteorol., 8:68-74.
13. National Academy of Science-National Research Council. 1966. Weather and Climate Modification: Problems and Prospects. Publ. No. 1350, NAS-NRS, Wash., DC, 232 p.
14. National Academy of Science-National Research Council. 1973. Weather and Climate Modification: Problems and Progress. NAS-NRS, Wash. DC, 258 p.
15. National Academy of Science-National Research Council. 1976. Climate and Food: Climatic Fluctuation and U.S. Agricultural Production, NAS-NRS, Wash, DC, 212 p.
16. Neyman, J., Osborn, H. B., Scott, E. L., and Wells, M. A. 1972. Reevaluation of the Arizona cloud seeding experiment. Proc. Nat'l. Acad. Sci., 69:1348-1352.
17. Neyman, J., and Osborn, H. B. 1971. Evidence of widespread effects of cloud seeding at two Arizona experiments. Proc. Nat'l. Acad. Sci., 68:649-652.
18. Neyman, J., Scott, E. D., and Smith, J. A. 1969. Areal spread of the effect of cloud seeding at the Whitetop experiment. Science, 163:1445-1449.
19. Schafer, V. J. 1946. The production of ice crystals in a cloud of supercooled water droplets. Science, 104(2707):459
20. Simpson, J., Woodley, W. L., Miller, A. A., and Cotton, G. F. 1971. Precipitation results of two randomized pyrotechnic cumulus seeding experiments. J. Appl. Meteorol., 10:526-544.
21. Simpson, J., Brier, G. W., and Simpson, R. H. 1967. Stormfury cumulus seeding experiment. J. Atmos. Sci., 24:508-521.
22. Summers, P. C., Elliott, R. D., Foehner, O. H., Davis, R. J., Grant, L. O, Griffith, D. A., and Keyes, C. G. 1983. Guidelines for cloud seeding to augment precipitation. ASCE J. Irrigation and Drainage Div., 109(1): 111-182.
23. Vonnequit, B. 1947. The nucleation of ice formation by silver iodide. J. Appl. Physics., 18:593-595.