9 October 1970, Volume 170, Number 3954

SCIENCE

Rainfall Enhancement by Dynamic Cloud Modification

Massive silver iodide seeding causes rainfall increases from single clouds over southern Florida.

William L. Woodley

There has recently been discussion on whether the relevant seeding technology is reliable for practical use (*1*). This question has proved a difficult one to resolve. Some of the confusion can be attributed to failure to recognize two major points: (i) there are essentially two approaches to seeding for precipitation increases, static and, more recently, dynamic, with each approach involving different seeding techniques and amounts of seeding material; and (ii) the seeding result depends on the initial conditions of the cloud-environment system. This article elaborates on these points in presenting the results of a new and exciting approach to cloud seeding for rain enhancement.

Background

Most cloud seeding efforts are predicated on producing instability in a supercooled cloud by introducing one artificial ice nucleus active at $-10°C$ per liter of cloud air. The artificially induced ice crystals then grow at the expense of the cloud water and, under ideal conditions, reach the ground as precipitation. This approach is referred to here as the static approach to cloud seeding (*1, 2*). Project Whitetop, analyzed rather extensively by Neyman *et al.* and by Flueck (*3*), is an example of static cloud seeding for rainfall enhancement. The results of such experimentation have been rather variable. Although some efforts have produced statistically significant precipitation increases, the results from some of the major experiments have been inconclusive and highly controversial.

An alternate approach to cloud seeding for precipitation enhancement is directed at the buoyancy forces and circulations that sustain the clouds; it is here referred to as dynamic cloud modification. This approach involves massive silver iodide seeding (100 to 1000 nuclei active at $-10°C$ per liter of cloud air) of individual supercooled cumulus clouds, which results in invigorated cloud dynamics through induced release of fusion heat. Dynamic cloud modification is not a new concept; it originated in the early days of weather modification (*4*). Dynamic seeding effects were observed so rarely prior to 1960, however, that serious doubt existed (*5*) as to the applicability of this seeding approach to rain enhancement.

The dynamic seeding hypothesis was not tested statistically until randomized cloud seeding experiments were conducted over the Caribbean in 1965 (*6*). Two main results emerged from the experimentation. First, massive seeding can, under predictable conditions, cause cumulus growth, and the cumulus model of the Experimental Meteorology Laboratory (EML) has considerable success in predicting this growth. Second, the seeding outcome depends on the initial conditions of the cloud-environment system. It was suspected, but not proved, that a cloud undergoing explosive growth would precipitate more than its unseeded counterpart. Verification had to await the sequels to this experiment.

Although not new by concept, the use of dynamic cloud modification in producing documented changes in precipitation is a new feature of recent experimentation in Florida and Arizona (*7*). As such, it represents a new approach to seeding for rain enhancement. The Florida study is the subject of this article.

Florida Program

Individual supercooled cumulus clouds growing over and near the Florida peninsula were seeded with silver iodide pyrotechnics in May 1968. The cooperative ESSA–Navy effort was conducted to study with aircraft and calibrated ground radars the induced dynamic and precipitation changes in the seeded clouds and to compare them with unseeded clouds, with both seeded and unseeded clouds chosen on a statistically randomized basis. Enumeration of project participants and a discussion of the experimental design and pyrotechnic seeding system can be found elsewhere (*8*).

There were 19 experimental clouds during the Florida program: 14 seeded clouds and 5 control clouds, as dictated by the randomized seeding instructions. Twenty 50-gram silver iodide pyrotechnics were dropped into each cloud —ten on each of two mutually perpendicular passes of the seeder aircraft near cloud top. The seeded clouds grew an average of 3500 meters more than the controls ($P < .01$) (*9*).

A typical instance of explosive cloud growth subsequent to seeding is shown in Fig. 1 for experimental cloud 5 on

The author is a research meteorologist in the Experimental Meteorology Laboratory, Atlantic Oceanographic and Meteorological Laboratories of the Environmental Science Services Administration (ESSA), at the University of Miami, Coral Gables, Florida 33124.

Table 1. Comparison of average rainfalls from seeded and control clouds 40 minutes after seeding pass. The last group of calculations is relative to the radar-measured rainfall in the 10-minute period before the seeding pass (taken as a standard in our measurement). RCC, radar control clouds.

	Rainfall from		Difference (acre-feet)	Difference (%)
	Seeded clouds (acre-feet)	Control clouds (acre-feet)		
	Water calculation (total)			
Without RCC	237	110	127	115
With RCC	237	97	140	144
	Water calculation (relative to standard)			
Without RCC	167	40	127	318
With RCC	167	49	118	241

19 May 1968. The rise rate of cloud top was computed photogrammetrically. Photographs of cloud development are shown as insets. Numbers along the rise rate curves correspond to the numbers of the photographs. Picture 1 was taken from 5500 meters above mean sea level, and all others were taken from 6100 meters.

Tower A of experimental cloud 5 was penetrated by a vertical stack of three aircraft at 1755 G.M.T. (Fig. 1, picture 1). After penetration, a fourth aircraft seeded towers A and B with a total of 1 kilogram of silver iodide smoke. In the 5 minutes after seeding, both towers became fuzzy and appeared to decay (Fig. 1, pictures 2 and 3). Subsequently, the upshear (southwest) portion of tower B hardened in appearance and grew to over 11,000 meters above mean sea level at a rate of 12 meters per second (Fig. 1, pictures 4 to 8). Predictions based on the EML dynamic cumulus model (*10*) indicate that experimental cloud 5 would not have behaved as it did had it not been seeded. This cloud produced 312 acre-feet of water in the 40 minutes after seeding compared with 87 acre-feet produced by the control cloud in the same time interval (*11*, *12*).

Calculating Cloud Rainfall

The main tool for measuring precipitation from the experimental clouds was the modified UM/10-cm radar of the Radar Meteorology Laboratory, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami. Its characteristics and operation are treated in detail by Senn and Courtright (*13*). This radar has a four-level iso-echo contour (IEC) unit that permits contouring of the signal strength of the experimental cloud echoes. An example is shown for part of the life cycle of experimental cloud 5 on 19 May 1968 (Fig. 2). Each contour corresponds to a discrete radar reflectivity Z ($mm^6 \, m^{-3}$), which was converted to the rainfall rate R ($mm \, hr^{-1}$) by using the Miami Z-R relation, $Z = 300 R^{1.4}$.

The technique of obtaining rainfall

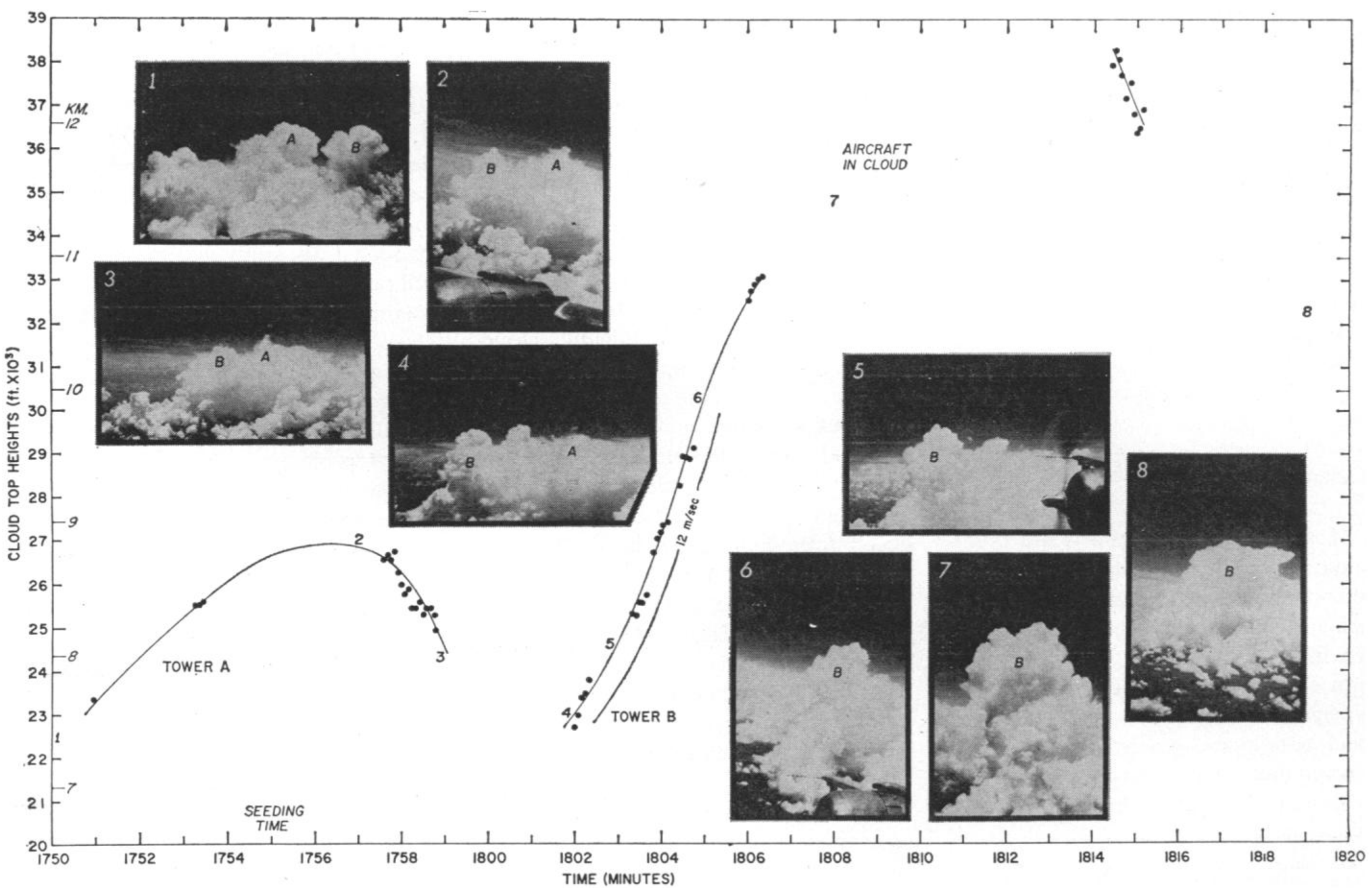

Fig. 1. Explosive growth of experimental cloud 5 (19 May 1968). Rise rates were computed photogrammetrically. Photographs shown as insets: picture 1 from 5500 meters above mean sea level; all other photographs from 6100 meters above mean sea level. Numbers along rise rate curves correspond to the numbers of the photographs.

has been discussed extensively (*11*). Essentially, it involves planimeter integration of the contoured target echoes to provide the total area contained between the contours, with each contour corresponding to a discrete rainfall rate. The contour areas are plotted versus time and are time-integrated. Multiplication of each time-integrated contour area by the appropriate mean rainfall rate and a constant, followed by summation, provides total rainfall during the period of integration. Radar calibration was provided by the scheme of Andrews and Senn (*14*). The rainfall analysis for an individual experimental cloud was discontinued when its echo merged with a neighbor. As a consequence, the analysis represents a bias in favor of the smaller, drier, nonmerging clouds. A representative cloud sample was possible to 40 minutes after the seeding pass. Five additional control clouds, conforming to the selection criteria for the experimental clouds, were included in the rainfall analysis (*11*). These clouds will be referred to as radar controls to distinguish them from the controls that were selected randomly.

Two comparisons were made between seeded and control rainfalls. First, total radar-measured rainfall from the seeded clouds in 10-minute intervals (after the time of the first seeding pass) was compared with rainfall from the control clouds. Second, the seeded and control clouds were compared among themselves and then with one another. The radar-measured rainfall from a given cloud in the 10-minute period before the seeding pass was taken as a standard, which was then subtracted from the radar-measured rainfall produced by the cloud in 10-minute intervals after the seeding pass.

Precipitation varied widely from cloud to cloud and from day to day, but, on the average, the seeded clouds precipitated twice as much as the control clouds, with the difference averaging between 100 and 150 acre-feet by 40 minutes after seeding (see Fig. 3a). The number in parentheses near each data point refers to the number of clouds contributing to the average. Inclusion of the five additional radar control clouds does not change the curves significantly. The average post-seeding total water from the seeded clouds exceeds that from the controls by at least a factor of 2 for each 10-minute interval.

Table 2. Statistical test of rainfall results. All tests were two-sided. RCC, radar control clouds.

Type of test	Significance (%)		
	Without RCC*	With RCC†	With RCC and mergers‡
Student's t	20	< 10	< 10
Normal scores	< 10	< 5	< 5
Wilcoxon-Mann-Whitney	< 20	< 10	< 10

* N_s (size of seeded sample) = 8; N_{ns} (size of nonseeded sample) = 4. † N_s = 8; N_{ns} = 9. ‡ N_s = 13; N_{ns} = 10.

The results of the analysis change little when the rainfall after the seeding pass is referenced to the rainfall in the 10-minute period before the seeding pass (Fig. 3b). The mean of referenced seeded rainfall is greater than control referenced rainfall in all time intervals.

Average rainfall from seeded clouds is compared with rainfall from the control clouds in Table 1. The differences would have been greater if calculations had been possible for entire cloud lifetimes.

The difference in mean total water between the seeded and control clouds 40 minutes after the seeding pass was tested for significance by (i) a pooled Student's t statistic with the variances assumed equal (a good assumption), (ii) the normal scores test, and (iii) the Wilcoxon-Mann-Whitney test. The results are shown in Table 2. In the last category (radar control clouds plus the mergers), the clouds that were dropped from the data sample because of mergers with surrounding echoes were assumed to persist in a steady state until 40 minutes after the seeding pass. The rainfalls produced by these clouds in the 10 minutes before they were dropped from the sample were assumed to fall in 10-minute intervals until the 40-minute cutoff. This artifice permitted all clouds to be retained in the sample, which resulted in a total population of 23 clouds. The significance of results from two-tailed tests increases with sample size. The results give strong support for the hypothesis that dynamic cloud modification increases precipitation. An alternate statistical approach to the problem (*11*) supports the conclusions reached above.

Accuracy of Rainfall Calculations

When radar is used in the evaluation of a cloud seeding experiment, it is necessary to determine how accurately the radar-derived precipitation changes represent real effects at the ground. The errors associated with the radar measurement of precipitation during May 1968 were evaluated by 50 direct comparisons of rainfall measured by radar and by rain gage (*15*). A direct comparison was not possible for the seeded clouds because none passed over

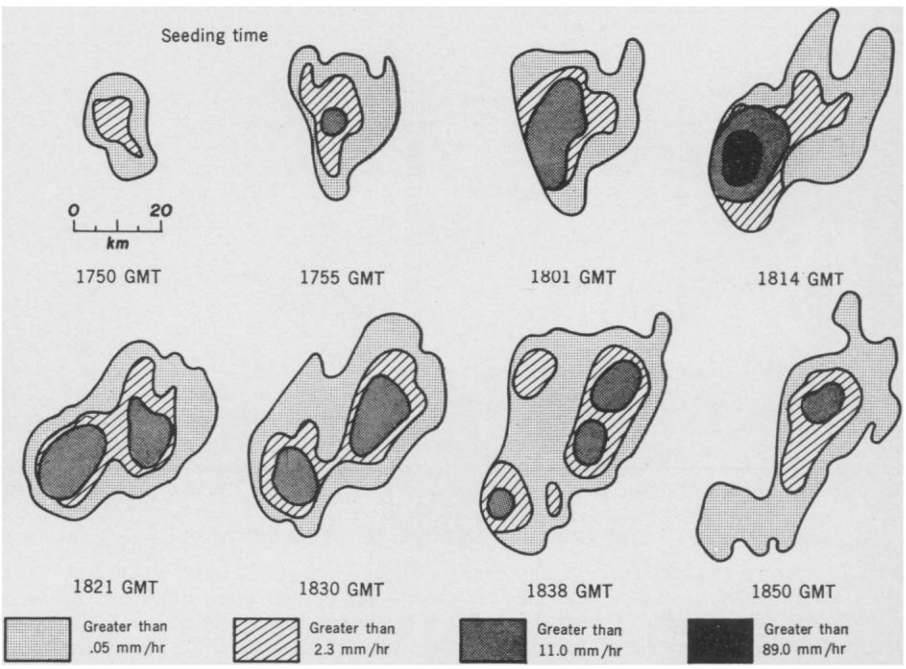

Fig. 2. Example of cloud base iso-echo contouring for cloud 5 (19 May 1968).

rain gages during the operation of the radar. Based on the rain gage as the standard, the average error is an 8 percent underestimate by the radar when the differences are summed algebraically and about 30 percent when their absolute values are summed. The average percentage difference is defined here as the average difference between the rainfalls measured by gage and radar divided by the average gage rainfall, rather than the mean of the individual percentage differences, in order to avoid giving undue weight to the few comparisons with small absolute differences but with large percentage differences. The correlation coefficient between the radar and gage rainfalls was 0.93 ($P < .01$).

The radar–rain gage comparison indicates that the radar in conjunction with the Miami Z-R relation gave a rather good approximation of unmodified shower rainfall. Because the Miami Z-R relation is just as valid for showers from seeded clouds (*11*), the radar represented seeded shower rainfall equally well; thus, the radar-derived precipitation increases probably represent real increases at the ground.

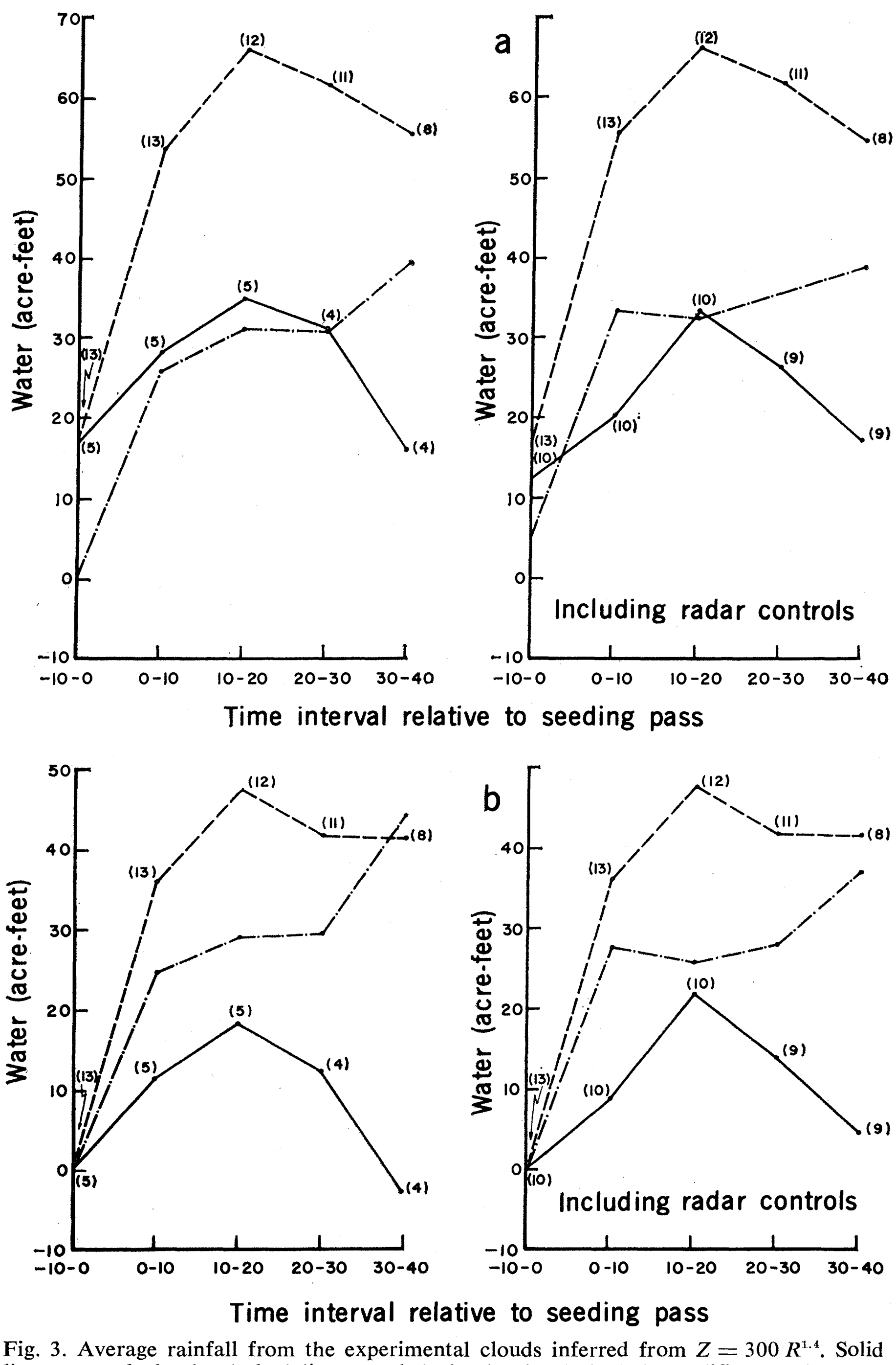

Fig. 3. Average rainfall from the experimental clouds inferred from $Z = 300\,R^{1.4}$. Solid lines, control clouds; dashed lines, seeded clouds; dot-dashed lines, difference between seeded and control clouds. Numbers in parentheses indicate the number of clouds in the sample. Time intervals are in minutes. (a) Average total water in 10-minute intervals relative to the time of the first seeding pass. (b) Average water relative to the water produced in the 10-minute period before the seeding pass.

Interpretation of Seeding Results

The amount of rain from the seeded clouds was positively correlated (correlation coefficient 0.90, $P < .01$) with the maximum top growth that followed seeding (*11*). The more a cloud grew after being seeded, the more rain it produced, which suggests that the precipitation increases were the result of the dynamic invigoration of the seeded clouds. The seeded clouds were larger and longer lasting; they processed more moisture than their unseeded counterparts and thus accounted for the increases in precipitation.

Cloud physics research revealed that the static approach to cloud seeding is apparently not applicable to supercooled Florida cumuli. All cumuli in which measurements were made had one ice particle per liter of cloud air at $-10°C$ *before* the seeding pass. Because the static approach to cloud seeding requires that this ice concentration be produced artificially for optimum results, this approach is not germane for cloud seeding over southern Florida. The dynamic approach worked despite the natural ice concentrations because there was still enough fusion heat potential in the smaller unfrozen drops to provide the impetus for dynamic changes induced by seeding.

This discussion is particularly pertinent to Project Whitetop, in which the static cloud seeding aproach was used in an attempt to increase rainfall. While researching basic cloud physics during the program, Braham (*16*) found natural ice concentrations as high as 10 particles per liter in Missouri cumuli with top temperatures of $\geqq -10°C$. In commenting on these findings, Braham noted, "The presence of numerous small particles in these clouds at temperatures warmer than $-10°C$ casts doubt upon the value of seeding with ice nuclei for rain inducement." Braham's finding may be a partial explanation for the failure of the static approach to produce rainfall increases from seeded Missouri cumuli. With respect to Whitetop, the relevant question is not whether seeding is reliable enough for practical use but whether seeding was done under conditions favoring precipitation increases. The answer to the latter, more pertinent question is apparently in the negative.

The failure of one cloud seeding approach in a region need not preclude the other. Dynamic cloud modification may be relevant for rain inducement from Missouri cumuli despite the failure of the static approach. McCarthy (*17*) has made a first step in resolving this uncertainty.

The discussion above is not an indictment of the static approach to cloud seeding for all areas and all seasons. This approach has been eminently successful in some areas—in Australia (*18*), for example—and there may be situations in which it is the only relevant approach to cloud seeding. The point for emphasis is that basic research must precede any seeding effort, whether it be static or dynamic, to determine which seeding approach, if any, is germane to producing the desired effect.

Stratification of the rainfall results of a seeding operation frequently provides information not obvious in initial examination of the data—as, for instance, in the analysis of the May 1968 Florida experiment. Large increases in precipitation were noted during the first half of the seeding program, which was characterized by fair conditions with only isolated natural showers. Little effect of seeding was noted during the second, naturally rainy half of the program (*19*). Dennis and Koscielski (*20*) had essentially the same result from a cloud seeding experiment in South Dakota, as did Davis *et al.* (*21*) in stratification of data obtained by Battan (*22*) during southern Arizona seeding operations. Preliminary analysis of Project Whitetop indicates a similar finding for Missouri (*23*).

The high positive correlation between cloud growth and water production suggests that a dynamic cumulus model that can predict cloud growth after seeding can also be used to infer the effect of seeding on precipitation. This effect has been quantified in terms of EML numerical model predictions by establishment of a relation between seedability (S) and the measured rainfall increase from seeding (ΔR) (see Fig. 4). Seedability is the predicted difference between the seeded and unseeded maximum top height of the same cloud. Rainfall decreases are found for seedabilities less than about 0.8 kilometer, but increases of several hundred acre-feet per cloud are associated with seedabilities above 3 kilometers. This

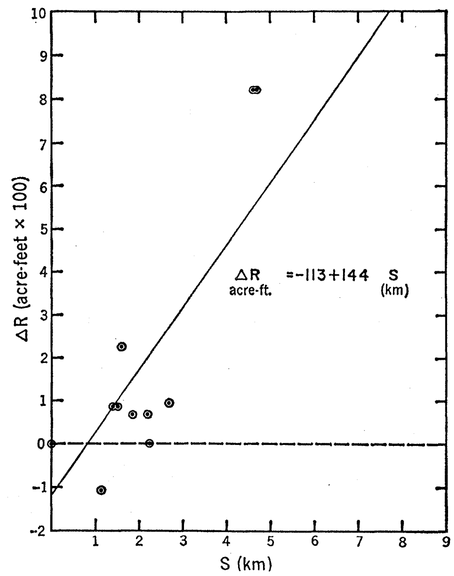

Fig. 4. Rainfall change (ΔR) as function of seedability (S).

finding is in agreement with the stratification of seeding results by weather regime because large seedabilities are characteristic of fair weather conditions with only isolated showers, whereas small seedabilities are characteristic of disturbed, naturally rainy conditions.

The relationship between S and ΔR indicates that the dynamic approach to cloud modification can produce both increases and decreases in rainfall under specified conditions. Further, it argues against blindly seeding all available clouds before some attempt has been been made to delineate favorable versus unfavorable seeding conditions.

Our results have shown that massive seeding of an individual cumulus cloud may increase rainfall by several hundred acre-feet per cloud, but it is important to know whether this increase represents a net increase, a decrease, or merely a redistribution of the rainfall over an area encompassing the seeded cloud. This uncertainty was investigated with two different approaches (*24*). The results showed that the large-scale effects of single cloud seeding were small precipitation increases, but severe data limitations and the low significance level of the increases ($P \sim .20$) do not allow much confidence in this result.

The success of massively seeding individual cumuli for precipitation increases does not necessarily imply its success on a larger scale. It must still be demonstrated that individual seedings of many supercooled cumuli are effective in altering cloud developments and precipitation over hundreds of square kilometers. To investigate this uncertainty, EML designed a multiple cloud seeding experiment for a target area of 5000 square kilometers in southern Florida (*25*), which was executed during July 1970. Acceptable experimental days satisfied a predetermined set of suitability criteria. Randomization was in time rather than in space. Radar was the main tool for precipitation evaluation.

Summary and Conclusions

In summary, the following points are made:

1) There are essentially two approaches to seeding for rain inducement, static and dynamic.

2) The dynamic approach is effective in inducing growth and increasing precipitation from individually seeded convective clouds under specifiable conditions.

3) The static approach to seeding for precipitation increases is apparently not relevant to the summer cumuli of Florida and Missouri.

4) Regional seeding climatologies, including studies of natural freezing processes in convective clouds, should be completed before commencement of a seeding operation.

5) The results of a seeding operation are frequently better understood by stratification of the data, especially with respect to weather conditions. Precipitation increases from seeding are usually found under fair weather regimes with isolated showers, whereas decreases are often noted under naturally rainy conditions.

It is premature to recommend routine use of dynamic modification as a practical means of increasing precipitation over large areas. Cloud and environmental conditions favoring large increases in precipitation must be better specified. Predictions by the EML numerical model, which indicate that large precipitation increases can be expected from clouds with large seedabilities, are a first step. The optimum amount of silver iodide for the desired effect is still to be specified. The effect of dynamic seeding on cloud developments and precipitation in the near and distant environments of the individually seeded clouds, and the precipitation effects of massively seeding many convective clouds over hundreds of square kilometers remain unknown.

Although it is still too early for a proper evaluation of dynamic cloud seeding as a routine tool for altering rainfall, first results are very encouraging. If dynamic seeding proves successful on a large scale over many regions of the globe, man will have taken a major step toward water management and the mitigation of severe storms.

References and Notes

1. J. Simpson, *Med. Opin. Rev.* **5**, 39 (1969).
2. M. Tribus, *Science* **168**, 201 (1970).
3. J. Neyman, E. Scott, J. A. Smith, *ibid.* **163**, 1445 (1969); J. A. Flueck, *Proc. First Nat. Conf. Weather Modification* (Albany, New York, 1968), pp. 26–35.
4. V. J. Schaefer, *Compendium of Meteorology* (Waverly, Baltimore, 1951), pp. 221–234; E. B. Kraus and P. Squires, *Nature* **159**, 489 (1947).
5. J. E. McDonald, *Advances in Geophysics* (Academic Press, New York, 1958), pp. 223–303.
6. J. S. Malkus and R. H. Simpson, *Science* **145**, 541 (1964).
7. A. J. Weinstein and P. B. MacCready, Jr., *J. Appl. Meteorol.* **8**, 936 (1969).
8. J. Simpson, W. L. Woodley, H. A. Friedman, T. W. Slusher, R. S. Scheffee, R. L. Steele, *ibid.* **9**, 109 (1970).
9. Symbol *P* represents the two-tailed significance probability.
10. J. Simpson and V. Wiggert, *Mon. Weather Rev.*, in press.
11. W. L. Woodley, *J. Appl. Meteorol.* **9**, 242 (1970).
12. 1 acre-foot $= 1.23 \times 10^3$ m$^3 = 1.23 \times 10^9$ grams of water.
13. H. V. Senn and C. L. Courtright, *Final Rep.* [Institute of Marine Sciences, University of Miami, Radar Meteorology Section, contract E22-62-68(N), 1968], 31 pp.
14. G. F. Andrews and H. V. Senn, *Proc. 13th Radar Meteorol. Conf.* (Montreal, Canada, 1968), pp. 20–23.
15. W. L. Woodley and A. Herndon, *J. Appl. Meteorol.* **9**, 258 (1970).
16. R. R. Braham, Jr., *J. Atmos. Sci.* **21**, 640 (1964).
17. J. McCarthy, *Proc. First Nat. Conf. Weather Modification* (Albany, New York, 1968), pp. 270–279.
18. F. D. Bethwaite, E. J. Smith, J. A. Warburton, K. J. Heffernan, *J. Appl. Meteorol.* **5**, 513 (1966).
19. J. Simpson, paper presented at the symposium on tropical meteorology (American Meteorological Society–World Meteorological Organization, Honolulu, Hawaii, 2–11 June 1970).
20. A. S. Dennis and A. Koscielski, *J. Appl. Meteorol.* **8**, 556 (1969).
21. L. G. Davis, J. I. Kelley, A. Weinstein, H. Nicholson, "Weather Modification Experiments in Arizona" [Report No. 12A of the Department of Meteorology, Pennsylvania State University, University Park (1968), 128 pp.].
22. L. J. Battan, *J. Appl. Meteorol.* **5**, 669 (1966); *ibid.* **6**, 317 (1967).
23. R. R. Braham, Jr., personal communication.
24. W. L. Woodley, A. Herndon, R. Schwartz, *ESSA Tech. Mem. ERLTM-AOML 5* (1969), 26 pp.
25. W. L. Woodley and R. Williamson, *ESSA Tech. Mem. ERLTM-AOML 7* (1970), 24 pp.

26. I thank Dr. Joanne Simpson, director of EML, and Alan Miller, Robert Powell, and Mrs. Suzanne Johnson for advice and assistance in writing this article.

Man and His Environment

Economic factors are more important than population growth in threatening the quality of American life.

Ansley J. Coale

The way our economy is organized is an essential cause, if not *the* essential cause, of air and water pollution, and of the ugly and sometimes destructive accumulation of trash. I believe it is also an important element in such dangerous human ecological interventions as changes in the biosphere resulting from the wholesale use of inorganic fertilizers, of the accumulation in various dangerous places such as the fatty tissue of fish and birds and mammals of incredibly stable insecticides. We can properly attribute such adverse effects to a combination of a high level of economic activity and the use of harmful technological practices that are inconsistent with such a high level.

The economist would say that harmful practices have occurred because of a disregard of what he would call *externalities*. An externality is defined as a consequence (good or bad) that does not enter the calculations of gain or loss by the person who undertakes an economic activity. It is typically a cost (or a benefit) of an activity that accrues to someone else. A fence erected in a suburban neighborhood for privacy also affords a measure of privacy to the neighbor—a cost or a benefit depending on how he feels about privacy versus keeping track of what goes on next door. Air pollution created by an industrial plant is a classic case of an externality; the operator of a factory producing noxious smoke imposes costs on everyone downwind, and pays none of these costs himself—they do not affect his balance sheet at all. This, I believe, is the basic economic factor that has a degrading effect on the environment: we have in general permitted economic activities without assessing the operator for their adverse effects. There has been no attempt to evaluate—and to charge for—externalities. As Boulding says, we pay people for the goods they produce, but do not make them pay for the bads.

To put the same point more simply: environmental deterioration has arisen to a large extent because we have treated pure air, pure water, and the disposal of waste as if they were free. They cannot be treated as free in a modern, urban, industrial society.

There are a number of different kinds of policies that would prevent, or at least reduce, the harmful side effects of some of our economic activities, either by preventing or reducing the volume of the harmful activity, or by inducing a change in technique. Other policies might involve curative rather than preventive steps, such as cleaning up trash along the highways, if we cannot prevent people from depositing it there.

Among the possibilities are steps that would make externalities internal. An example that I find appealing, although it is perhaps not widely practical, is to require users of flowing water to take in the water downstream of their operation and discharge it upstream. A more general measure is to require the recycling of air or water used in industrial processes, rather than permitting the free use of fresh water and clean air, combined with the unmonitored discharge of exhaust products.

Public authorities can charge for unfavorable external effects by imposing a tax on operations that are harmful to the environment. The purpose of such taxes is to reduce the volume of adverse effects by inducing a shift in technique or by reducing the volume of production by causing a rise in

The author is director of the Office of Population Research at Princeton University, Princeton, New Jersey 08540.

This article is adapted from a talk given 19 March 1970 at a symposium devoted to "Man and Environment" at the University of North Carolina, Chapel Hill.