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Seeding Cumulus in Florida: New 1970 Results

Rainfall increases from single cloud seeding are conclusive; next is multiple seeding to promote "mergers."

Joanne Simpson and William L. Woodley

Dynamic cumulus seeding and the promising apparent rainfall increases that resulted from a randomized single cloud seeding experiment in Florida in 1968 have recently been described (*1*). Briefly, dynamic seeding involves massive doses of artificial freezing nuclei (silver iodide), which is usually introduced into the tops of supercooled cumuli by dropping pyrotechnic flares (*2*) from aircraft. The purpose of the massive seeding (100 to 1000 active nuclei per liter at $-10°C$) is to rapidly release all the latent heat of freezing available in the cloud's supercooled water and thus to increase the buoyancy or growth forces. The dynamic seeding experiments of the National Oceanic and Atmospheric Administration (NOAA) have been based on a one-dimensional computer model of a cumulus tower, which predicts that in tropical areas dynamic seeding can often cause large growth of the cloud (more than 3 kilometers in the vertical).

Pioneering seeding work in 1963 with this model was described in 1964 (*3*). Since then two randomized experiments have been conducted, in 1965 and 1968. They revealed that the initial conditions of the cloud-environment system determine which of four possible growth regimes will follow dynamic seeding. In descending order, the regimes are explosive growth, hesitation growth, cutoff tower growth, and no growth (*4*). The experiments showed conclusively that dynamic seeding can cause considerable vertical growth under specifiable conditions and that the model has considerable success in predicting its amount. Now that it has been improved to treat the growth of precipitation (*5*), the model also has considerable success in predicting internal properties of both modified and unmodified clouds (*6*). The most important contribution of the model is, however, the concept of "seedability"—the predicted top height difference (in kilometers) between the seeded and unseeded cloud. Not only were these model predictions confirmed in 1965 and 1968, but the model-predicted seedability was shown to be highly correlated with the measured rainfall differences between seeded and control clouds (*1*). This result epitomizes the most important point regarding dynamic seeding; namely, what causes seeded clouds to rain more is the increased cloud size and lifetime rather than direct changes in microphysics or rainfall rate.

Use of a calibrated ground radar with the 1968 Florida seeding data showed that, for the first 40 minutes after the seeding run, seeded clouds precipitated an average of 100 to 150 acre-feet more than did the controls, a difference of about 100 percent (*7*). Because the cloud sample was too small, however, the statistical significance of the rainfall differences was marginal; it ranged from 5 to 20 percent with several different two-tailed tests.

1970 Florida Single Cloud Experiments: Design and Execution

To enlarge the previous sample, the NOAA-Navy group planned to conduct an improved repeat of the 1968 single cloud experiment from 15 April to 31 May 1970. We also planned our first attempt at a randomized multiple cloud seeding effort.

For the single cloud experiment, there were two major design improvements. (i) Seeding took place from a better instrumented aircraft that carried the project scientists instead of from a less equipped, two-man aircraft that was directed by radar. Both of us rode behind the pilots, and one (W.L.W.) pressed the seeding button at roughly 100-meter intervals in the part of the cloud that was active and had a high water content. The delivery racks were armed or disarmed in the rear of the aircraft by a "randomizer," who opened in secret the sealed envelopes containing the decisions. The envelopes were prepared by a statistician (*8*) to say "seed" or "no seed" according to a procedure roughly similar to tossing a coin (but where long strings of successive identical instructions were precluded). (ii) An attempt was made to randomize in pairs to obtain seeded and control clouds that were better matched than was the case in 1968.

Execution of the 1970 experiments was beset by difficulties. A serious public relations problem arose, largely because of unusually heavy March rains. Vegetable growers, conservationists, and cattlemen of south Florida became alarmed at the prospect of a cloud seeding program to follow on the heels of floods. Particularly upset were the to-

Dr. Simpson is director of the Experimental Meteorology Laboratory, National Oceanic and Atmospheric Administration, and adjunct professor of atmospheric science, University of Miami, Coral Gables, Florida 33124. Dr. Woodley is a research meteorologist at the Experimental Meteorology Laboratory.

mato farmers, whose harvest was extended into the experimental period; any rainfall during harvest badly damages tomatoes. The multiple cloud seeding program had to be postponed until July, and the single cloud experiment was allowed to proceed but with severe restrictions in area.

Both experiments were salvaged through the selection of impartial observers to monitor the experiments on behalf of the growers. The observers were agricultural agents of the Dade County Extension Service (*9*) for Vegetable and Fruit Crops, one of whom was in the Radar Laboratory during all operations to keep track of the aircraft and seeded clouds. A separate report is being prepared on the public relations developments (*10*).

Compounding the public relations difficulties were unfavorable weather conditions during April and May. A drought set in from 1 April to 20 May, during which no seedable clouds presented themselves. The drought was broken on 20 May by Tropical Storm Alma, and from then through 31 May conditions were highly disturbed. Layers of clouds commonly made seeding impossible, and high natural growth made seedabilities small. From 15 April to 31 May, there were four operational days, three of which provided a seeded sample under disturbed weather conditions.

The second phase of the experiment was executed between 29 June and 19 July 1970. There were no public relations problems, and the weather was only slightly more unfavorable than normal. The multiple seeding was given priority, but we were able to obtain three single cloud days in this period and 2 days on which a single cloud experiment was combined with the multiple cloud experiment. The only disadvantage of the combination was the sacrifice of a matching number of seeded and control clouds on some days.

Real time predictions of the numerical model were used to guide the flight operations. The latest version (*11*) was run each day with the early morning (1200 G.M.T. or 0800 E.D.T.) Miami radiosonde observation. Flights were usually launched on days when seedabilities exceeded 1 kilometer for one or more horizontal tower diameters. Only six flights were made without seeding, out of a potential 59, and no seedable days were missed.

Altogether there were nine operational days in 1970 on which the single cloud seeding experiment was conducted. The details of the operation and data analyses are given elsewhere (*12, 13*). The locations of the experimental clouds with respect to the University of Miami radar are shown in Fig. 1. A case study of each cloud, with photographs, appears in a more detailed report (*12*) together with tabulations of the "before and after" measurements and documentation of ambient conditions. Twenty-nine single clouds were obtained: 13 seeded, 6 random controls, and 10 radar controls (*1*). By comparison, in 1968 there were 14 seeded clouds, 5 random controls, and 5 radar controls. In 1970, the average radar control rainfall exceeded that of random controls by 1.7 acre-feet (0.8 percent); on 4 of the 5 days when both random and radar controls occurred, the radar controls were wetter and more vigorous. In 1968 and 1970 together, radar controls were 6 percent wetter on the average than were random controls.

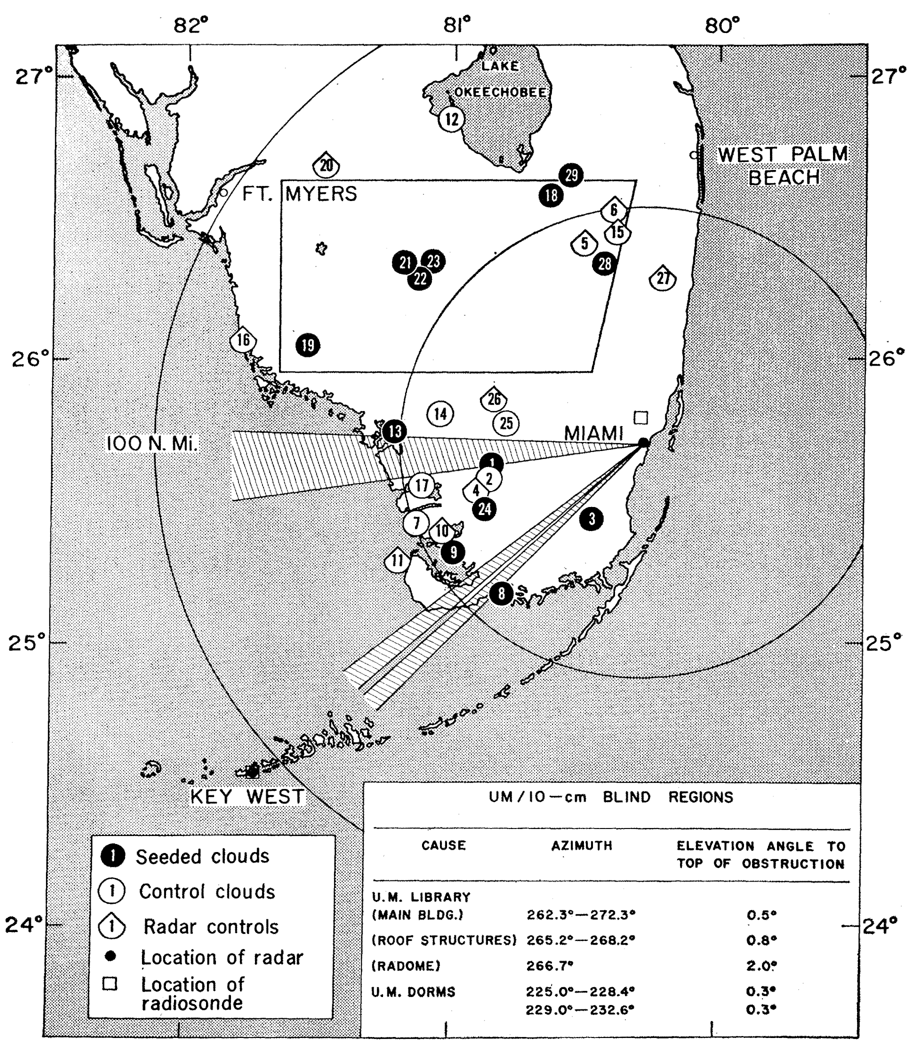


Fig. 1. Location of clouds used in Florida single cloud seeding experiment 1970. The blind cones in the University of Miami calibrated 10-centimeter radar are also shown. The quadrilateral to the south of Lake Okeechobee (2700 square nautical miles) is the target area for the multiple cloud seeding experiment.

Radar Systems, Analysis Methods, Problems, and Mean Results

The unique, modified 10-centimeter radar of the University of Miami, its calibration and operation in the experiment, have been described in detail elsewhere (*1, 14*). Briefly, rainfall is evaluated by measuring echo areas at cloud base (about 2500 feet, or 760 meters) and by integrating these over time. This method has been tested by a radar-rain gauge comparison (*15*); it has also been shown that the spectrum of raindrops is no different for seeded and control clouds (*14*).

There were more analysis problems with the 1970 radar data than there were in 1968 because three seeded clouds moved into radar blind cones (Fig. 1) or ground clutter. Their rainfall was evaluated by means of approximations described in detail elsewhere (*12, 13*). An attempted repeat of the radar-rain gauge calibration also suggested that the underestimation of the heavy rains by the radar may have been more severe than it was in 1968. We can show, however, that the conclusions in this article would be strengthened rather than weakened by elimination of all these errors and approximations (*13*).

Table 1 compares the mean total seeded and unseeded rainfalls for the first 40 minutes after seeding and for the total cloud lifetimes. The former measure was chosen because few mergers occurred prior to 40 minutes after seeding. Despite all our efforts to avoid them in both years, 14 experimental cloud echoes merged with neighbors and had to be dropped from the analysis after the time of merger. There were nine seeded mergers and five controls, so that the effect of the truncated analyses was, if anything, to bias the results against seeded clouds.

For the first 40 minutes the average seeded minus control difference is about 100 acre-feet (see Table 1), an increase of about 55 to 75 percent. For the whole cloud lifetimes, the difference exceeds 250 acre-feet, or considerably more than 100 percent. The important question is whether these seeded-control differences can be attributed to the seeding. The results of the statistical significance tests (*16*) confirm the causal relationship. In all the tests shown in Table 1, the fourth roots of the rainfall amounts were taken in order to minimize the effects of nonnormality and to make the statistical models more applicable in view of known day-to-day variations in seeding effect.

The first test is the Wilcoxon-Mann-Whitney, which does not require a normal distribution of data. With this test, the combined 1968 and 1970 results are significant at the 0.5 percent level for both the first 40 minutes and the total cloud lifetimes. The 1970 results alone are significant at the 10 and 5 percent levels, respectively. The second test is a covariate regression. The total transformed rainfall of the control clouds after the seeding run is plotted as a function of that of the 10 minutes before the seeding run, and a linear regression is fitted. The resulting equation is used to predict the total (transformed) seeded rainfall, the predicted and observed quantities are subtracted, and the significance of the difference is tested. The low values demonstrate that seeded and control populations differ significantly, particularly when the 1968 and 1970 data are combined.

The third test, analysis of covariance, is performed by plotting the total (transformed) rainfall after the seeding run versus that for the 10 minutes before the seeding run separately for seeded and control clouds. A linear regression is fitted to each set of points, and the difference between the two lines is tested for significance. The results of this test are less satisfactory than the others, owing to inhomogeneity between the 1968 and 1970 control cloud populations (*17*). The fourth test examines the differences between seeded and control mean (transformed) rainfalls on each day averaged over all days, with allowance made for the fact that there were unequal numbers of seeded and control clouds on many days.

A quantitative measure of the seeding effect in terms of the nontransformed data is obtained as follows: The original R (total) seeded amounts are multiplied by a suitable constant (< 1.0) such that the estimated seeding effect is identically zero when these reduced values are transformed by the fourth root and reanalyzed, as was done in the analysis of daily means. For the combined 1968 and 1970 data, this constant is approximately 0.3; that is, seeding increased the precipitation by a factor greater than 3. It is interesting to compare this result with the last line of Table 1. The factor by which we must multiply $\bar{R}_{ns}$ (163.3 acre-feet) to obtain $\bar{R}_s$ (433.8 acre-feet) turns out to be 2.7, in good agreement with the value derived by sounder statistical methods.

Again in 1970 the data show that the seeded clouds rained more than the controls because they were bigger, longer-lasting clouds. In 1970 seeded clouds averaged 19 percent taller and 75 percent larger in area, and their echoes lived 56 percent longer than did the control cloud echoes. Multiplying these factors together gives 3.2, in fine agreement with the statistical estimate of the 1970 seeding factor and with the rougher estimate from Table 1.

Table 1. Summary of rainfall results from single cloud seeding. Average rainfall $\bar{R}$ after seeding is given in acre-feet. Symbols: n, number of cases; R_s, seeded rainfall; R_{ns}, control rainfall. Significance tests: 1, Wilcoxon-Mann-Whitney; 2, covariate regression; 3, analysis of covariance; 4, analysis of daily means. (All tests are one-tailed, with significance equal to or better than the values listed.)

Year	Seeded		Unseeded		Average difference	Significance			
	n	$\bar{R}_s$	n	$\bar{R}_{ns}$	$(\bar{R}_s - \bar{R}_{ns})$	1	2	3	4
				0 to 40 minutes after seeding					
1970	13	258.4	16	164.0	94.4	.10	.10	.10	.05
1968 and 1970	26	249.3	26	140.8	108.5	.005	.005	.05	.005
				Total cloud lifetimes after seeding					
1970	13	490.8	16	204.8	286.0	.05	.05	.10	.01
1968 and 1970	26	433.8	26	163.3	270.5	.005	.01	.05	.005

Table 2. Stratification of total rainfall results: mean rainfall $\bar{R}$ in acre-feet. Significance was calculated by means of the Wilcoxon-Mann-Whitney test (all tests are one-tailed, with significance equal to or better than the values listed). Symbols: n, number of cases; R_s, seeded rainfall; R_{ns}, control rainfall.

Stratification	Seeded		Unseeded		Average difference	Significance
	n	$\bar{R}_s$	n	$\bar{R}_{ns}$	$(\bar{R}_s - \bar{R}_{ns})$	
			1968 and 1970			
Fair	22	458.7	20	89.1	369.6	.005
Rainy	4	297.1	6	411.4	−114.3	
All	26	433.8	26	163.3	270.5	.005
			1970			
Fair	10	519.6	11	74.0	445.6	.005
Rainy	3	395.0	5	492.7	−97.7	
All	13	490.8	16	204.8	286.0	.05

Fair Versus Rainy and Intraday Comparisons

From our 1968 results it appeared that the dynamic seeding effects were much larger on fair than on rainy days (*1, 11*). We now stratify our data in terms of an objective criterion (*12, 13*). A rainy day is defined to occur when 12.7 percent of the south Florida area is covered by precipitating clouds. All radar echoes within a radius of 100 nautical miles of Miami are planimetered on a radarscope; a coverage exceeding 4000 square nautical miles at 1800 G.M.T. qualifies the day as rainy (*18*). This boundary is consistent with tropical rainfall studies (*19*), which show that 50 percent of the total rain falls on 10 percent of the days with rain; it is this 10 percent that we have defined as rainy.

Table 2 shows the effect of this stratification on the amounts of seeded and control rainfall and their differences. The important result is that on fair days the rainfall increases due to seeding are in the range of 330 to 400 acre-feet, or of the order of 400 percent of the unseeded clouds' precipitation. The differences are significant at the 0.5 percent level. On rainy days it appears that seeding may actually decrease rainfall, although the rainy sample is not large enough to test significance. In going from a fair to a rainy day, the control cloud precipitation increases three to six times, partly because, even initially, rather narrow towers naturally reach cumulonimbus stature on disturbed days. Also, with two clouds having the same top height, the one in the disturbed environment probably rains more owing to smaller concentrations of condensation nuclei (*20*).

Furthermore, Table 2 suggests that, in going from a fair to a rainy day, seeded clouds rain less. With the 1968 data, we found that in south Florida rainy days are commonly associated with rapid wind changes in the vertical, called wind shear. Strong shear inhibits the explosive growth of seeded clouds and restricts the length of their lifetimes (*11*). In 1970 the mean shear (850 to 200 millibars) was nearly 50 percent stronger on rainy than on fair days, and seeded cloud lifetimes were one-third shorter.

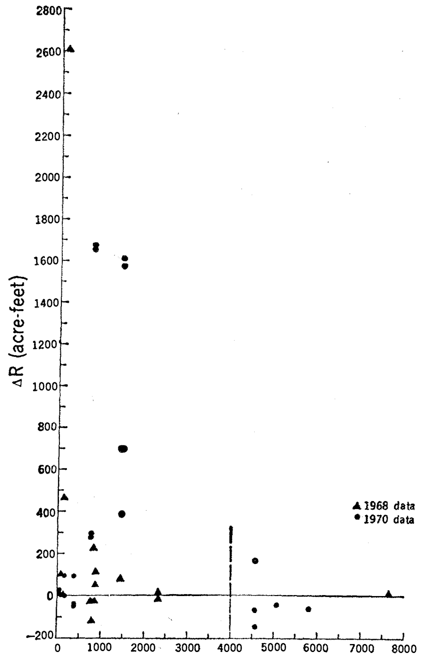


Fig. 2. All seeded minus control pairs, ΔR, for all permutations each day for the whole cloud lifetime or until merger, plotted against echo area coverage at 1800 G.M.T. within a radius of 100 nautical miles of Miami. This area coverage is proportional to degree of disturbance or "raininess"; the boundary between "fair" and "rainy" is defined as a coverage of 4000 square nautical miles (vertical dashed line), which is about 12.7 percent of the total area.

Next, intraday rainfall differences are computed by permuting all seeded clouds with all controls, which results (for example) in four pairs on a day with two seeded and two control clouds. In case of merger, the paired comparison is truncated at the time of merger. The results of this analysis are presented in Table 3 ("all permutations"). Unfortunately, the results of this scheme cannot be subjected to statistical tests because the pairs generated in this way are not independent. Intraday mean seeded minus control differences were obtained by calculating mean seeded and control rainfall for the day and then subtracting (Table 3, "Intraday mean"). Thus only one difference is obtained per day, which drastically decreases the sample size. However, the mean of the intraday differences can be tested statistically. For 1970 alone the significance is marginal (10 percent level), but it is satisfactory (5 percent level or better) when 1968 and 1970 are combined. The seeded and control differences vary little between all permutations and intraday means (Table 3). On fair days the differences range from 370 acre-feet to above 550 acre-feet, whereas they are small and negative for rainy days. For fair and rainy days together, the mean differences range from 270 acre-feet to above 400 acre-feet, which is equal to or higher than overall mean differences in Table 1.

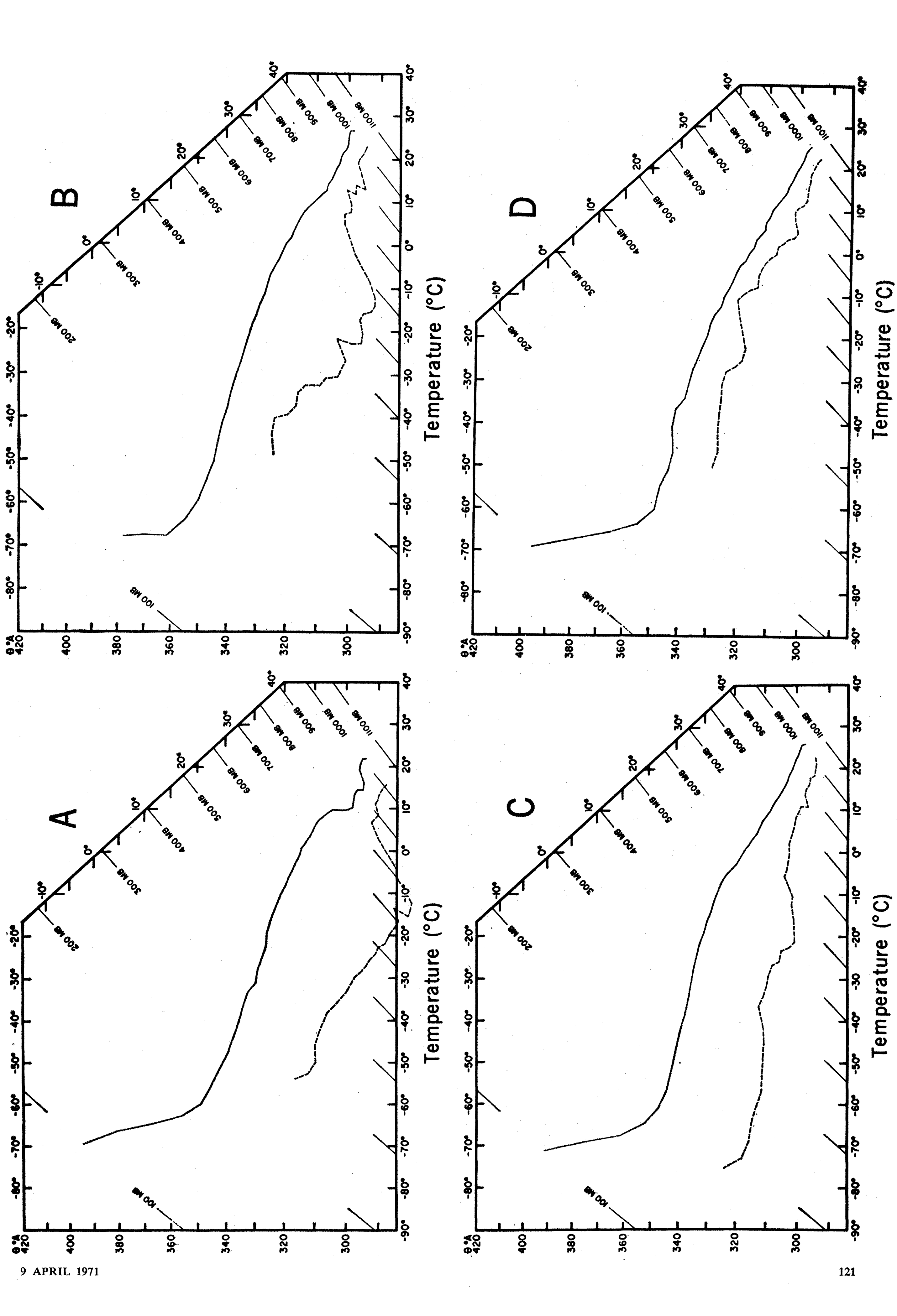
In Fig. 2 all seeded minus control pairs ΔR's (for all permutations) are plotted against degree of disturbance or "raininess." With one exception, all disturbed ΔR's are either negative or zero. The fair ΔR's consist of nine very large values ($\geqq$ 400 acre-feet), five moderately large values ($100 < R < 400$ acre-feet), and 15 small or negative values ($\Delta R \leqq 100$ acre-feet). Therefore, a fair day is a necessary but not a sufficient condition for large rainfall increases from seeding individual clouds.

The small and negative ΔR's in Fig. 2 were analyzed. One was a case of a seeded cloud that died without growth.

Table 3. Stratification of total rainfall results: intraday comparisons of mean rainfall $\bar{R}$ in acre-feet. Symbols: n, number of cases; R_s, seeded rainfall; R_{ns}, control rainfall. Significance test: 1, t-test for paired comparisons; 2, Wilcoxon signed rank test. (All tests are one-tailed, with significance levels equal to or better than the values listed.)

Stratification	Mean difference all permutations		Mean of intraday mean difference		Significance	
	n	$\bar{R}_s - \bar{R}_{ns}$	n	$\bar{\bar{R}}_s - \bar{\bar{R}}_{ns}$	1	2
1968 and 1970						
Fair	29	432.6	13	369.6	.025	.004
Rainy	6	−22.2	4	−54.6		
All	35	354.6	17	269.8	.025	.01
1970						
Fair	16	557.2	6	561.2	.05	.02
Rainy	5	−27.5	3	−74.1		
All	21	418.0	9	349.4	.10	.08

Fig. 3 (opposite page). Mean soundings (composite radiosonde observations) for four different cumulus growth regimes in the tropics. The soundings are plotted on tephigrams (potential temperature, abscissa; actual temperature, ordinate). The temperature curves are the solid lines; the dew point temperature curves are the dashed lines. (A) Suppressed growth (seven soundings). (B) Cutoff tower growth (four soundings). (C) Explosive growth (six soundings). (D) Large natural growth (eight soundings).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Nine were cases in which the cutoff tower regime followed seeding, and in five cases either the seeded or control echo merged, which forced early termination of the analysis. Fortunately, cutoff tower situations can now be diagnosed with our numerical model (*11*) or even, fairly well, by inspection of the radiosonde observation only (see next section).

Cloud Growth

In the 1970 experiment the 13 seeded clouds all grew to cumulonimbus stature —that is, above 31,000 feet (1 foot = 30.48 centimeters). Five clouds exhibited the cutoff tower growth mode, two exhibited hesitation growth, and six grew explosively. Of the 16 control clouds, ten reached cumulonimbus stature. The seeded clouds grew an average of 14,000 feet after the seeding run, and the control clouds grew an average of 7800 feet. The difference of 6200 feet is significant at the 1 percent level. This figure is to be compared with a difference of 5200 feet in 1965 and 11,400 feet in 1968. In 1965, one-third of the seeded clouds failed to grow (owing to poor seedability), whereas in 1968 the random controls grew an average of only 1100 feet after the seeding run and four out of five failed to reach cumulonimbus stature. The 1970 control sample is probably more representative of unmodified supercooled Florida clouds. The inhomogeneity between 1968 and 1970 control clouds caused some difficulty in the analysis of covariance (Table 1).

Now that the randomized dynamic seeding experiment on single clouds has been conducted three times on a total of 28 operating days, and 76 clouds selected by the precise statistical procedure described (41 seeded and 35 controls) have been studied in detail, we can construct mean soundings that typify the atmospheric conditions prevailing with each growth regime (Fig. 3). Figure 3A illustrates the typical condition when cumulus growth is suppressed. On days like this one, cloud tops do not reach the seeding level (about 21,000 feet or − 10°C). When the inversion and drying are at a somewhat higher elevation, cumuli may reach the seeding level but seedability is small or zero. Figure 3B illustrates the typical sounding for the cutoff tower regime. The extremely dry stable layer in midlevels causes the seeded tower to separate from the cloud body; wind shear is not necessary for this growth mode to prevail. In Fig. 3C we see the most favorable conditions for dynamic seeding. Here there is a weak stable layer in midlevels, which restricts natural growth, and an unstable upper troposphere. Seeded clouds with this environment commonly explode in two phases. The first is a vertical growth to an altitude of 35,000 to 45,000 feet, which requires 10 to 15 minutes, and the second is a horizontal expansion, which requires another 15 to 20 minutes (*3*). The resulting giant cumulonimbus may persist for 2 hours or more. The sounding in Fig. 3D is typical of rainy disturbed conditions, where seedabilities are again small, here owing to large natural cloud growth. In south Florida, these conditions are often, perhaps usually, accompanied by strong vertical shear, which inhibits explosive growth.

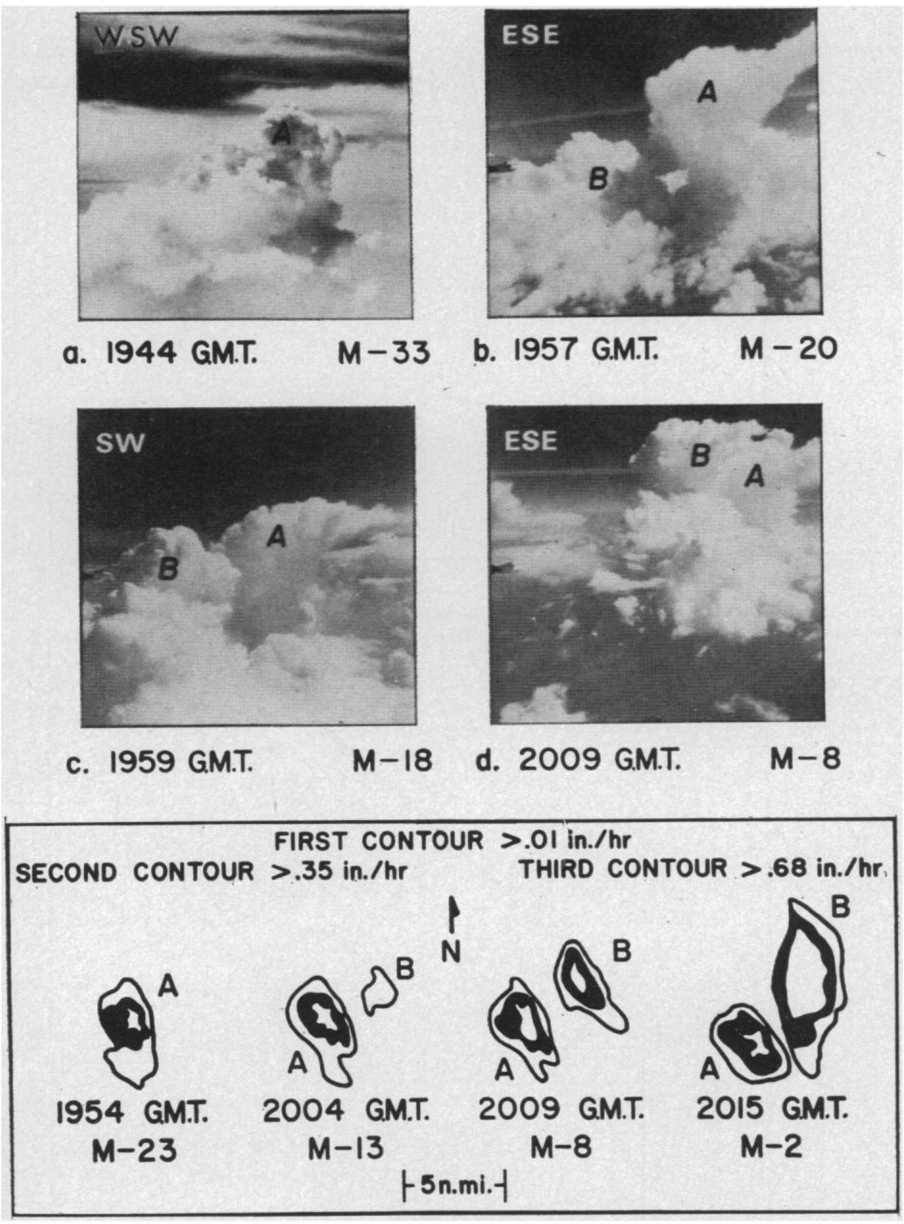


Fig. 4. (Top) Before merger (*M*) photographs of clouds A (seeded) and B (unseeded) on 16 July 1970, taken from seeder aircraft at an elevation of 21,000 feet. The camera direction is indicated in the upper left of each photograph. The numbers below each panel are the times in minutes relative to the time of merger. (a) Seeded cloud (A) 26 minutes after seeding and 33 minutes before merger with cloud B. Cloud A, exhibiting "hesitation growth," is entering its main growth phase at this time. (b) Cloud A has attained miniature cumulonimbus stature. Cloud B is growing rapidly. (c) Cloud B has become the more vigorous cloud. (d) Both clouds have attained cumulonimbus stature but have not yet merged on radar. (Bottom) Precipitation histories of clouds A and B before merger. Depictions were constructed from photographs of the University of Miami 10-centimeter radarscope as the antenna scanned 0.5° elevation, which corresponds to a beam center altitude of 3500 feet at the range of these clouds. Note rapid growth of cloud B relative to cloud A.

The Next Steps: Mergers and What They Suggest

The question that now arises is how best to utilize these single cloud results, both toward improved water management and toward understanding (perhaps, one day, modifying) the organization of cumuli into systems and storms. The Florida single cloud experiments have had mainly a scientific motivation, but important clues to these next steps have already come from them. Ironically, the merger cases that plagued the single cloud rainfall evaluations have proved to be the most informative. The most striking feature of mergers is the great increase in water production that frequently follows.

As an illustration, a brief discussion of one of the more interesting mergers of two initially isolated clouds is presented in Figs. 4 and 5. Cloud A was seeded; cloud B was not. Both clouds paced one another to great heights, with the seeded cloud reaching 41,000 feet before merger. After merger, the consolidated cloud system reached 53,000 feet. The radar depictions of the two clouds during their merger phase is shown in Fig. 5 (bottom). The area of the system increased with time, as did the area covered by the innermost intense cores. In its most intense phase the merged system covered over 100 square nautical miles.

The merger of the seeded cloud with its neighbor resulted in a great increase in precipitation production compared with what the component clouds produced prior to merger (Fig. 6). This merger also produced an order of magnitude more precipitation than isolated clouds on this day. A specific comparison is presented in Table 4 for the merger case and the two isolated control clouds. Although all clouds surpassed 40,000 feet, it would have taken 36 isolated clouds to equal the precipitation of the merged system!

From this and other merger cases (*21*) it became apparent that our efforts at rain enhancement would be most successful if the seeding could promote the formation of cloud mergers and other more complicated but potentially more productive cloud systems. It also became apparent that merger and organization are probably the first necessary steps in the formation of squall lines, tropical storm rainbands, and the giant cumulonimbus systems that fuel the large-scale equatorial air motions (*19*). These organized "cloud clusters" play so large a role in driving the planetary circulations that they will be the main focus of the tropical experiment of the Global Atmospheric Research Program planned for 1974 (*22*).

Multiple Cloud Seeding Experiment

From 29 June to 19 July 1970, we executed a pilot project in multiple cloud seeding over south Florida. This program had two goals: (i) to determine whether the precipitation increases produced by massive seeding of isolated cumulus clouds can be enhanced by seeding 20 to 30 clouds in rapid succession over a fixed target; and (ii) to arrive at a better understanding of cloud interaction, whether seeded or non-

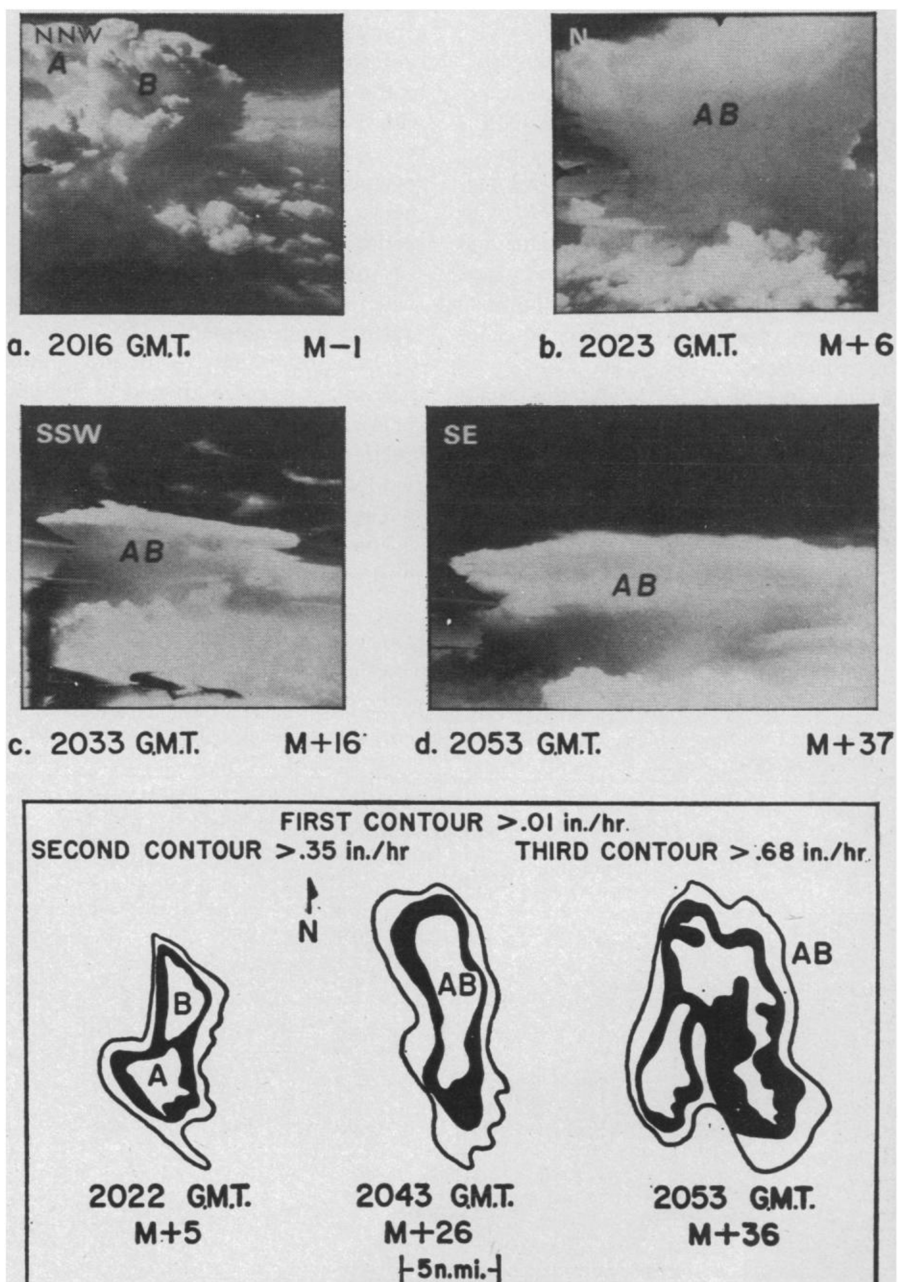


Fig. 5. (Top) After merger (*M*) photographs of clouds A (seeded) and B (unseeded) on 16 July 1970, taken from the seeder aircraft at an elevation of 21,000 feet. The camera direction is indicated in the upper left of each photograph. The numbers below each panel are the times in minutes relative to the time of merger. (a) Clouds 1 minute before merger on radar (see Fig. 4d). Note pileus (cap cloud indicating vigorous growth) near the tops of both clouds. (b) Clouds 6 minutes after merger seen in the upshear direction under the anvil. (c) Clouds A and B have lost identity as the merger has become a massive thunderstorm complex. (d) The complex 37 minutes after merger. (Bottom) Precipitation history of clouds A and B after merger on the University of Miami 10-centimeter radar, as in Fig. 4, bottom.

Table 4. Comparisons of single clouds (A and B) with a merger (16 July 1970).

Measurements	Before merger		After merger of A and B	Control cloud	Radar control cloud
	A	B			
Maximum top height (feet)	41,000	45,000	>50,000	47,000	41,000
Total rainfall (acre-feet)	242.5	124.0	8797.6	244.3	147.8
Lifetime on 10-cm radar (min)	35	14	112	59	43

seeded, to begin attempts at mesoscale modeling.

The design of the experiment can best be understood with a flow diagram (Fig. 7). The design features (*23*) included:

1) A fixed target area (Fig. 1) with randomization weighted two to one in favor of seeding.

2) Surveillance of the clouds in the target by both 5-centimeter and 10-centimeter radars of the University of Miami (*14*).

3) Suitable days for experimentation were those that satisfied an objective "meteorological suitability factor" (MSF) of $S - N_e \geqq 1.0$, where S is the maximum predicted seedability (in kilometers) predicted by our model (*11*) with the 1200 G.M.T. Miami radiosonde and a hierarchy of horizontal cloud sizes, and N_e is the number of hours between 1300 and 1600 G.M.T. with 10-centimeter echoes in the target. The maximum value of N_e is 3, and this factor is introduced to bias the decision for experimentation against naturally rainy days. Decision time on a day's suitability was 1600 G.M.T.

4) The seeder aircraft flew on all days that satisfied the meteorological suitability factor. The seeding decision was randomly determined in the air when suitable clouds were found in the target, with only the "randomizer" knowing the decision.

5) Final acceptance of a day for inclusion in the area analysis was made only after expenditure of 60 flares (50 grams of silver iodide each) or after seedings of six clouds, or both.

Multiple seedings of individual clouds in close proximity were attempted to promote mergers and to enhance the preferred organization patterns evident in the unmodified convection. On days with adequately long cloud lifetimes, these attempts frequently had apparent spectacular success. Six area experiments were conducted in 1970 (four seed days and two control days). There was one radar control day when the seeder aircraft was forced to abort owing to a malfunction.

The rainfall analyses for the multiple experiment were completed in the same manner as for the single clouds (*1, 14*). Their results, which were presented in two talks in 1970 (*24*), are summarized in Table 5.

Total target rainfall (Table 5) is the most straightforward and easily understood measure of the effects of seeding. However, it can sometimes be misleading. On several days large nonexperimental precipitating clouds either formed or moved into the target area. They were in no way the result of the seeding operations, but they were included in the rainfall analysis by virtue of their presence in the target.

The "floating target" rainfall analysis (Table 5) is more sensitive because it is limited to the experimental clouds and to those clouds with which they merge. The analysis area floats or moves with the clouds. In all cases, however, the floating target is bounded by the fixed target. A successful experiment in rain enhancement is one in which the floating target rainfall is large and in which the ratio W_{FT}/W_{TT} of floating target to total target rainfall approaches 1.

Other measures of the effects of seeding are the rate of precipitation development (dR/dt) and the depth of water in the floating target (Table 5). The latter was computed in 10-minute intervals by dividing floating target water by the mean area of the floating target. Although this is only a crude estimate of the actual water depth, it is clear that some of the rainfall amounts are not small; on two seeded days amounts exceed 2 inches (5 centimeters) and on one of them they approach 4 inches (10 centimeters).

If the method of stratification were an accurate indicator of the degree of disturbance and if seeding had no effect, then we would expect the most disturbed

Table 5. Rainfall summary of 1970 multiple cloud seeding experiment 5 hours after initial seeding. In column 2, MSF indicates the meteorological suitability factor. Area coverage (column 3) indicates coverage at 1800 G.M.T. of radar echoes with a radius of 100 nautical miles of Miami. Under "Total AgI," parentheses denote a control day; numbers within parentheses give the amount of AgI that would have been expended had we been seeding. W_{FT}/W_{TT}, ratio of floating target to total target rainfall; dR/dt, rate of precipitation development in first hour after initial seeding.

Day	MSF ($S - N_e$)	Area coverage (square nautical miles)	Time of seeding (G.M.T.)		Total AgI (g)	Total target rainfall (acre-feet × 10^4)	Floating target rainfall (acre-feet × 10^4)	W_{FT}/W_{TT}	Water depth floating target (inches)	dR/dt (acre-feet/min)	Sum of ranks
			First	Last							
29 June	2.95	1000	1743	2058	6800	1.41	0.16	0.11	1.29	7.4	25
Rank						6	6	6	4	3	
30 June *	1.10	4145	1714	1950	(6050)	6.06	3.08	0.51	2.72	22.4	15
Rank						4	3	4	2	2	
2 July	5.00	710	2036	2302	4800	1.71	1.12	0.65	1.20	64.3	17
Rank						5	4	2	5	1	
7 July	2.85	550	1835	2113	(6300)	6.13	0.73	0.12	1.06	3.1	24
Rank						3	5	5	6	5	
8 July	3.70	1275	1756	2005	7550	8.08	6.41	0.79	2.38	4.2	10
Rank						1	1	1	3	4	
17 July	1.90	775	1800		0	3.75					
Rank											
18 July	2.90	42	1851	2136	6750	7.53	4.37	0.58	3.91	0.9	14
Rank						2	2	3	1	6	

* The most disturbed day (the only "rainy" day).

day to rank first in total target rainfall. Instead, seed days rank first and second in this quantity and the most disturbed day ranks fourth. However, a seed day also ranks last in total target rainfall. The magnitude of total target rainfall ranges between 10^4 and 10^5 acre-feet of water during the 5-hour analysis period, one to two orders of magnitude greater than the maximum amount of rainfall that is observed from intense isolated Florida thunderstorms during their lifetimes.

There is some reshuffling of positions when floating target rainfalls are ranked, but the two most prolific days are still seed days. The least prolific day is also a seed day. With this ranking, three of the first four positions are occupied by seed days.

The ratio of floating target to total target rainfalls is especially interesting (Table 5). A successful day is one on which most of the total target rainfall falls in the floating target. By this criterion, the three most successful days are seed days, and it is a near draw between a seed and nonseed day for the least successful designation.

The measure of mean intensity of the rainfall in the floating target is the depth of water there. A seed day and a nonseed day are first and second in this ranking, and the most prolific day in terms of floating target rainfall is third because of its much greater target area.

The last method of evaluation is the rate of precipitation development during the hour after the initial seeding. Again, a seed day and a nonseed day rank first and second, and it is 2 July 1970 that ranks first. On this day, it was obvious in real time that seeding was having an immediate effect on the clouds.

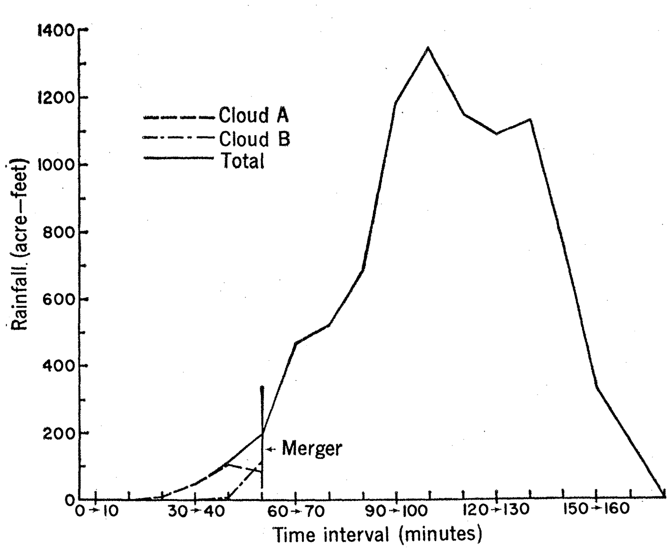
To assess the overall success of the experiment according to the five criteria, the ranks for each day were summed and then compared (Table 5). The two most successful days were seed days followed closely by the most disturbed day, a control, and then a seed day. The two least successful days were a seed and a control day in that order.

Although the sample size does not permit definitive conclusions, the results are encouraging and are consistent with expectations. Three of the four most successful days as defined were seed days, and the control day was by far the most naturally disturbed. The poor showing of the seeding on 29 June 1970 is presently a puzzle but will undoubtedly be clarified by the synoptic study (already in progress) of the events on this day. It is probably related to the factor causing short cloud lifetimes, which frustrated merger attempts.

Summary

In the Florida single cloud experiments, the main result of the statistical analyses is that the dynamic seeding effect on rainfall is large, positive, and significant. From all the 1968 and 1970 data together, the seeding effect is estimated to be larger than a factor of 3; that is, the seeded clouds rained more than three times as much as the controls after the seeding run. On fair days, defined objectively by percentage of area covered by showers, the seeding effect is shown to be larger than the overall average, but it may be negative on rainy days. Rainy days in the tropics are about 10 percent of the days with rain, but they produce about half the total rainfall. The applicability of our single cloud results to other areas is not established but seems hopeful for many tropical and subtropical regions. It can be assessed by cloud population studies together with our numerical model (*25*).

Guidance for the next steps toward practical rainfall enhancement and toward the understanding and modification of cloud systems in storms may be provided by our study of merger clouds.



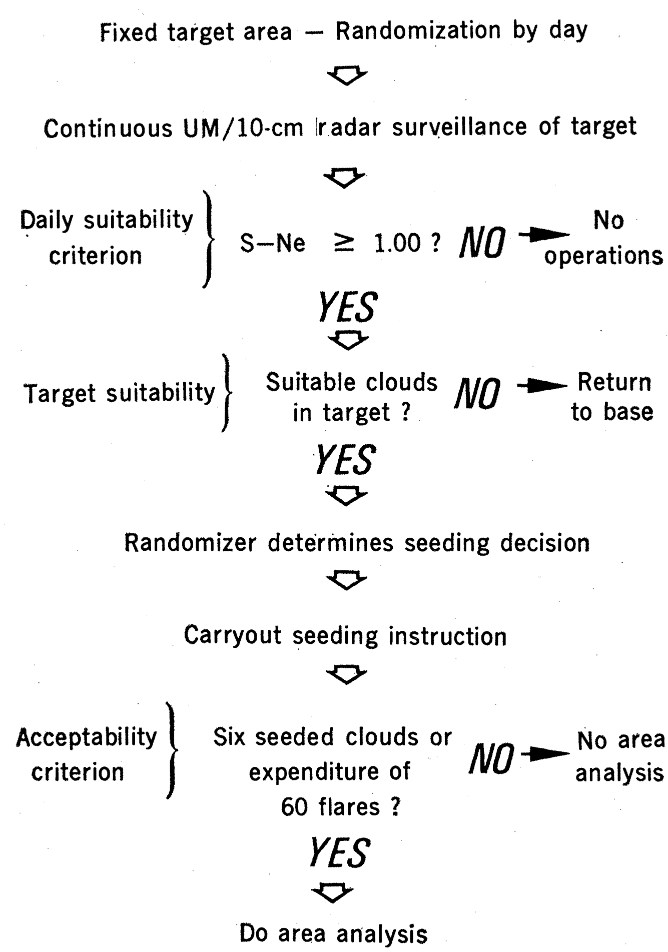


Fig. 6 (left). Precipitation histories of clouds A and B before and after merger (vertical line) on the University of Miami 10-centimeter radarscope, 16 July 1970. Rainfall is plotted against time (10-minute intervals relative to seeding cloud A).

Fig. 7 (right). Flow diagram showing the design of the 1970 multiple cloud seeding experiment. [For details, see (*23*).]

Mergers are shown often to produce more than an order of magnitude more rain than isolated clouds on the same day, probably owing to dynamic invigoration of the merged cloud circulations. Results of our first small attempt toward inducing and documenting mergers in a multiple cloud seeding experiment appear promising. Although far from statistically conclusive, they have opened a new frontier in the science and technology of dynamic cloud modification. It is also hoped that the multiple cumulus seeding experiments will help to clarify the formation of "cloud clusters" and their role in large-scale circulations, thus contributing to the focal subject of the Global Atmospheric Research Program in the tropics.

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Archeological Methodology and Remote Sensing

Tests of aerial remote-sensing devices have revealed varying degrees of usefulness to the archeologist.

George J. Gumerman and Thomas R. Lyons

For millions of years man and his ancestors have efficiently utilized their auditory and visual systems as remote-sensing devices for gathering information about the environment. Furthermore, man has probably always realized that his overall perception can be increased by stepping back a few paces and looking from a distance. Remote sensing, then, in the normal sense refers to the acquisition of data from the physical environment by means of a data-gathering system at some distance from the phenomena being investigated. In a much broader sense, remote sensing today encompasses an entire system including data acquisition, data reduction, interpretation, and explanation. The most common mechanical data-acquisition systems are aerial cameras, which utilize various types of film, and the more recently developed scanning devices and radiometers, all of which measure particular wavelength spans within the electromagnetic spectrum.

All materials at temperatures above absolute zero in the natural environment produce electromagnetic radiation in the form of waves. The electromagnetic spectrum is a continuum of natural (passive) and induced (active) radiation in wavelengths varying from fractions of a micrometer to kilometers. There is no single device, including the human eye, which can detect emissions within the entire electromagnetic spectrum, and consequently the spectrum has been somewhat arbitrarily divided into a number of broad categories. These subdivisions range from the very short-wavelength cosmic rays (10^{-16} to 10^{-14} meter) to the very long-wavelength radio waves (10 to 10^5 meters). Between these extremes lie the visible and the near-, intermediate-, and far-infrared portions of the spectrum, which are of particular interest in any data-gathering system applicable to archeological problems.

In an effort to judge for archeological research purposes the imaged output and the correlative value of various aerial remote-sensing devices, the American Southwest was chosen as a major test area. This is an area of vast

Dr. Gumerman is director of the Archaeological Survey and assistant professor of anthropology at Prescott College, Prescott, Arizona. Dr. Lyons is assistant director of the Technical Applications Center, University of New Mexico, Albuquerque, New Mexico, and acting director of the National Park Service Chaco Canyon Research Center.