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Rainfall Results, 1970–1975: Florida Area Cumulus Experiment

Massive seeding with silver iodide alters the rainfall from convective cloud groups over the target area.

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During the summer of 1975 the Cumulus Group of the National Hurricane and Experimental Meteorology Laboratory, National Oceanic and Atmospheric Administration, continued the series of cloud-seeding experiments known as the Florida Area Cumulus Experiment (FACE). As discussed in (*1*), the FACE program is an outgrowth of a series of experiments in Florida in which individual clouds were seeded; these experiments demonstrated beyond reasonable doubt that "dynamic seeding" is effective in increasing the sizes and lifetimes of individual cumuli and the rainfall resulting from them by nearly a mean factor of 3. As presently conceived, this program is designed to determine whether dynamic seeding can be used to augment convective precipitation over an extensive area in south Florida [1.3×10^4 square kilometers (see Fig. 1)] by promoting larger and better organized convective systems. Various aspects of the FACE program prior to 1975 have been treated in detail by Woodley and Sax (*2*). Progressive updates on the rainfall results of FACE have also been reported (*1, 3, 4*).

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Background

Dynamic seeding with massive amounts of silver iodide (100 to 1000 grams per cloud), as used in FACE, invigorates the circulations that sustain the supercooled convective clouds. This technique is predicated on the rapid conversion of supercooled liquid water to ice during the active growth phase of a cloud. The resulting release of latent heat increases cloud buoyancy. Evidence from the Florida single-cloud studies suggests that the increased buoyancy invigorates the cloud and prolongs its lifetime, resulting in increased convergence at cloud base, a greater mass flow through the system, and, in consequence, a more efficient processing of the available moisture together with an augmentation of the rainfall. The hypothesis underlying FACE is that, under optimum conditions, dynamic seeding eventually leads to better organization of the low-level inflow, better cloud organization through a merger process, and areawide enhancement of the rainfall. This chain of reasoning is being examined in a stepwise fashion in FACE (*2*).

Cloud merger, or the joining of two formerly independent cloud entities, is apparently the crucial natural process leading to heavy and extensive convective rainfall in Florida. Consequently, dynamic seeding must be effective in promoting this natural process if it is to augment areal rainfall. In designing FACE, we decided to investigate two sequential questions: Can dynamic seeding be used to systematically induce cloud merger and increase rainfall from the groups of subject clouds, and can dynamic seeding be used to produce a net increase in rainfall over a fixed target area? An affirmative answer to the first question is a necessary, but perhaps insufficient, condition for an affirmative answer to the second.

In FACE a random experimental design is used, which involves randomization of days over a single target area into seed and nonseed days, with nonseed days as the control. The experiments began on a limited basis in 1970 with 6 days of randomized experimentation (hereafter called "GO" days). The study continued in 1971 with an additional 6 GO days, in 1973 with 12 GO days, and in 1975 with 24 GO days.

The Design of FACE

The design features of FACE include:

1) A fixed target area (Fig. 1) with the experiments randomized by day.

2) Surveillance of the clouds in the target by 10-centimeter radars of the University of Miami (in 1970 and 1971) and the National Hurricane Center (NHC) (in 1973 and 1975), with radar estimation of the rainfall (rain estimates were adjusted with the use of rain gages).

3) The determination of suitable days for experimentation on the basis of a daily suitability criterion of $S - N_e \geq 1.5$, where S is the seedability (the difference in kilometers between the maximum height of a cloud if seeded and the same cloud if not seeded) predicted by the one-dimensional cloud model developed at the Experimental Meteorology Laboratory (*5*) with the 1200 G.M.T. Miami radiosonde and a hierarchy of horizontal cloud sizes, and N_e (earliness) is the number of hours between 1300 and 1600 G.M.T. with 10-centimeter echoes in the target. The N_e factor is introduced to bias the decision for experimentation against naturally rainy days. Consequently, optimal days for seeding are those on which the seedability is large and the natural rainfall early in the day is small.

4) Flights by the seeder aircraft on

days that satisfy the above criterion. (The seeding decision was randomly determined in the air when vigorous clouds with active updrafts and hard outlines, high water content, and top temperatures near −10°C were found in the target, with only the "randomizer" knowing the decision.) Suitable convective clouds are seeded near their tops.

5) Final acceptance of a day for inclusion in the area analysis only after the ejection of 60 flares (50 to 70 grams of silver iodide each) or after the seeding of six clouds, or both.

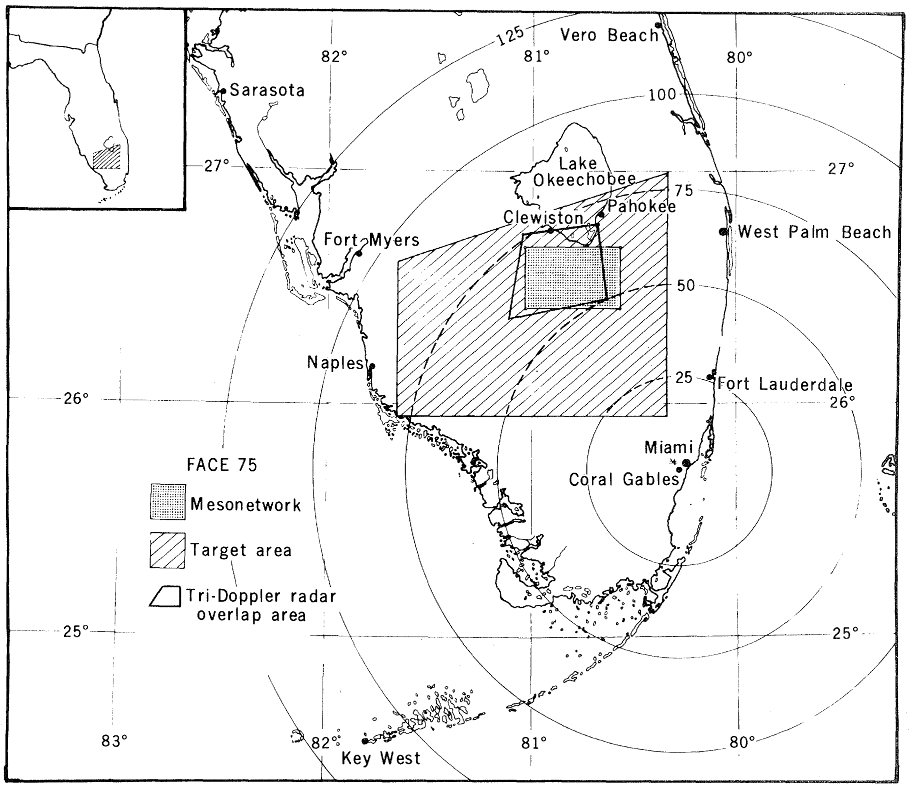

Fig. 1. Field design for FACE 1975. The mesonetwork is the area in which several types of surface meteorological measurements were made. The target area refers to the area over which randomized seedings took place. The tri-Doppler radar overlap area is the area scanned by the three Doppler radars in FACE 1975. Distances from Miami are given in nautical miles.

Table 1. Measurements for FACE 1975; NS, not seeded; S, seeded.

Date	Action	$S - N_e$	c (%)	p ($m^3 \times 10^7$)	FT ($m^3 \times 10^7$)	TT ($m^3 \times 10^7$)	Echo motion category
6/21	NS	1.75	13.4	0.274	12.85	15.53	2
6/22	S	2.70	37.9	1.267	5.52	7.27	1
6/24	S	4.10	3.9	0.198	6.29	7.45	2
6/25	NS	2.35	5.3	0.526	6.11	10.39	1
6/27	S	4.25	7.1	0.250	2.45	4.70	1
6/30	NS	1.60	6.9	0.018	3.61	4.50	2
7/9	NS	1.30	4.6	0.307	0.47	3.44	1
7/16	NS	3.35	4.9	0.194	4.56	5.70	1
7/18	NS	2.85	12.1	0.751	6.35	8.24	1
7/19	S	2.20	5.2	0.084	5.06	7.30	1
7/20	S	4.40	4.1	0.236	2.76	4.05	1
7/23	S	3.10	2.8	0.214	4.05	4.46	1
7/24	NS	3.95	6.8	0.796	5.74	6.73	1
7/26	S	2.90	3.0	0.124	4.84	9.70	1
7/29	S	2.05	7.0	0.144	11.86	15.10	1
7/30	NS	4.00	11.3	0.398	4.45	6.21	1
8/13	NS	3.35	4.2	0.237	3.66	7.58	2
8/15	S	3.70	3.3	0.96	4.22	8.51	1
8/16	NS	3.80	2.2	0.23	1.16	4.17	1
8/19	S	3.40	6.5	0.142	5.45	8.13	2
8/25	S	3.15	3.1	0.073	2.02	2.20	1
8/28	NS	3.15	2.6	0.136	0.82	1.09	1
9/11	S	4.01	8.3	0.123	1.09	2.16	1
9/12	NS	4.65	7.4	0.168	0.28	3.50	1

Multiple seedings of individual clouds in close proximity to one another were attempted to promote mergers and thus to enhance the preferred organization patterns evident in the unmodified convection. On days with adequately long cloud lifetimes, these attempts were apparently successful.

For all the FACE experimentation, 48 GO days have been obtained on which the weather conditions warranted the ejection of more than 60 flares, including 26 random seed days and 22 random control days. The rainfall results and their interpretation for these days are discussed in this article.

Evaluation of Rainfall on GO Days

The estimation of convective rainfall in FACE with the Miami reflectivity-rainfall rate relation has received extensive treatment (*6*). The 10-centimeter radar of the Radar Meteorology Laboratory of the University of Miami was used to evaluate the series of single-cloud seeding experiments between 1968 and 1971. By 1973, the primary research radar being used was the NHC WSR-57. Radar was chosen for the evaluation of the single-cloud seeding experiments because rain gage measurement of rainfall from individual clouds (base echo areas generally about 250 square kilometers) could not have been accomplished without an enormous expenditure of money and logistic effort. Moreover, seed and control clouds were selected on each experimentation day, and so, despite radar inaccuracies, intraday relative differences (seed versus control) should still have been valid. For the area experiment and interday randomization, radar is not as obvious a choice, particularly if it exhibits great interday variability. Woodley *et al.* (*6*) treated this problem in detail and concluded that radar is the best tool for the evaluation of rainfall in FACE, provided that the radar estimates are adjusted by rain gages. Olsen and Woodley (*7*) have shown that the existing measurement errors are very much less than the magnitude of the rain variability problem and do not substantially add to the uncertainties.

In the analysis of the FACE experimentation days, rainfall calculations were carried out for the floating and total targets for 1 hour before and 6 hours after the initial seeding. The floating target is composed of the echoes of all subject clouds (that is, those clouds for which the button that initiates seeding was pushed when the aircraft penetrated the cloud) and those with which they merge. The total target includes the floating target echoes plus the echoes of nonsubject clouds within the target. All rain calculations are limited to the target area.

The floating target concept was used for several reasons. Early work in FACE showed that it was impossible to seed all clouds in the target area at the moment that they became suitable, even with two seeder aircraft. Once a seeding opportunity was missed, the cloud either dissipated or grew to massive size by itself. In either case, seeding was in no way responsible for cloud behavior and the presence of such a cloud in the target area merely diluted any seeding effect there. At the time there was no way to determine the magnitude of this problem, and the floating target was devised to serve as a more sensitive measure of the effect of seeding than the total target, a means of determining whether dynamic seeding is effective in promoting cloud merger and rainfall and also a safeguard against years of fruitless seeding experimentation.

Rainfall Results Before 1975

Prior to 1975 the only statistically significant evidence supporting the seeding hypothesis was derived from an analysis of 276 single subject clouds examined during the course of the FACE experiments (*3*). Stratification of the results depended on whether the single clouds dissipated in the target area without merger or whether a particular cloud merged with a neighbor. For clouds that never merged, the mean seeded rainfall exceeded the mean control rainfall by a factor of 2, a result (one-tailed significance of 3 percent) that is consistent with earlier single-cloud studies (*1*). No meaningful rainfall comparison was possible for clouds that merged because, on the average, the seeded clouds merged (and the analysis was terminated) 13 minutes earlier than the controls. This disparity in mean cloud lifetime before merger (two-tailed significance of 0.5 percent) suggests that seeding promotes merger in FACE as intended. We now have evidence, as presented here, that the more rapid merger of the seeded clouds leads to greater rainfall in the floating target and in the overall target area.

The most important result of FACE 1973 was the discovery of a significant covariate, namely, the motion of precipitation echoes as "seen" by radar. It was possible to stratify experimentation days into moving echo days (category 1) and stationary echo days (category 2) by viewing the time-lapse photographs of the WSR-57 radarscope. This echo motion classification was conducted independently by two individuals not involved in the rainfall analyses. Echo motion is related in a complicated way to the mean wind in the atmospheric layer containing the echoes; in general, the greater the mean wind, the greater the echo motion, but there are exceptions. Consequently, interpretation of the results of the echo motion covariate in terms of mean layer winds may not be valid.

Simpson and Woodley (*3*) showed by one-way analysis of variance that echo motion is a statistically significant covariate for both floating and total target rainfall. Subsequently, Biondini (*8*) reanalyzed the Florida single-cloud experiment, using echo motion as a covariate. He found strong evidence that seeding effects depend on the echo motion category. Although the effect of dynamic seeding on single-cloud rainfall was shown to be positive in both echo motion categories, seeding on moving echo days led primarily to an increased variance in the sample. On stationary echo days a multiplicative seeding factor (seeding increased rainfall by a constant multiplicative factor) remained plausible. Most important, the stratification of experimentation days into echo motion categories and the single-cloud reexamination provided the clues necessary to obtain some statistically significant results and to formulate some tentative physical hypotheses.

Rainfall Data in 1975

In the summer of 1975 (between 16 June and 15 September) ten subprograms and a core-seeding program of FACE were in progress; rainfall results from the 1975 core experiment are presented in Table 1. Echo coverage (c) is the percentage of the Miami radarscope covered with echo [within a radius of 100 nautical miles (1 nautical mile = 1850 meters)] at 1400 E.D.T. A disturbed day is defined as $c > 13$ percent; we attempted to screen as many of these days as possible out of the sample. Prewetness (p) is the target area rainfall during the 1 hour preceding the first seeding run; *FT* is the rain in the floating target for 6 hours after the first seeding, and *TT* represents the corresponding rain volume for the total target.

Table 2 presents sample means ($\bar{R}$) and standard deviations (σ) for all FACE GO days from 1970 through 1975 without data stratification. There is evidence in

Table 2. Means and standard deviations for the rain results for FACE 1970–1975 (units of cubic meters × 10^7); N, number of days; $\bar{R}_S$, mean rainfall on seed days; $\bar{R}_{NS}$, mean rainfall on control days.

Action	*FT*					*TT*				
	N	$\bar{R}$	σ	$\bar{R}_S/\bar{R}_{NS}$	Significance*	N	$\bar{R}$	σ	$\bar{R}_S/\bar{R}_{NS}$	Significance*
Seed	26	3.74	3.21	1.18	0.26, 0.24, 0.25	26	5.72	3.97	0.94	0.63, 0.70, 0.30
Control	22	3.17	3.02			22	6.08	3.76		

*One-tailed significance of difference in mean rainfall; the first number was obtained with the t test without data transformation, the second number was obtained with the t test after a fourth-root transformation of the data, and the third number was obtained with a Mann-Whitney (Wilcoxon) U test for two samples.

Table 3. Rainfall results for FACE 1970–1975 stratified by echo motion category (in units of cubic meters × 10^7); N_S, number of seed days; N_{NS}, number of nonseed days.

Parameter calculated	Seed*			Random control			$\bar{R}_s/\bar{R}_c$
	$\bar{R}$	σ	v	$\bar{R}$	σ	v	
	Category 1, moving echoes: $N_S = 19$; $N_{NS} = 14$						
FT	3.108	2.921	0.94	2.586	2.358	0.91	1.20
TT	5.020	3.763	0.75	4.440	2.777	0.63	1.13
NFT	1.912	1.488	0.78	1.854	1.190	0.64	1.03
	Category 2, stationary echoes: $N_S = 6$; $N_{NS} = 8$						
FT	5.442	3.881	0.71	4.185	3.906	0.93	1.30
TT	7.690	4.565	0.59	8.951	3.650	0.41	0.86
NFT	2.248	1.413	0.63	4.766	2.838	0.60	0.47

*Disturbed seeded outlier (22 June 1975) excluded.

Table 2 for a positive effect in the floating target and little, if any, effect in the total target. No result is significant at the 5 percent level.

Table 3 presents the rainfall results for 1970 through 1975 stratified by echo motion category. The coefficient of variation (v) is the ratio of the standard deviation to the sample mean. The term *NFT* refers to the "nonfloating target," which is made up of the echoes within the target that are not experimental echoes.

When the data across categories are studied, it is obvious that the mean rainfall is naturally greater in the stationary echo category than in the moving echo category. In fact, a mean difference of 2 between the total target control rainfall in the motion and no-motion categories is significant at better than the 1 percent level when a t-test is used.

Examination of the data within categories (Table 3) permits an assessment of the seeding effect. In category 1, both means and variances are larger for seeded as compared to unseeded days. In category 2, the seeded floating target exhibits a larger mean than the control, whereas the situation is reversed in the total target. The greatest difference in the category 2 cases lies in the much larger control nonfloating target rainfall as compared with the seeded case—a puzzling result. There is little difference in the variances of the floating targets, but in the total target the seed variance is larger than that of the control. The opposite is true for nonfloating target variances.

Biondini *et al.* (9) used the four covariates discussed earlier [seedability (S), earliness (N_e), prewetness (p), and echo coverage (c)] in a stepwise regression program to obtain an empirically derived simple function of these variables that can be used to predict natural, unseeded rainfall. In most cases, a two-, three-, or (at most) four-term model was produced, which accounted for 75 percent or more of the variability in the data. We estimated and analyzed "seeding effects" on the basis of an examination of the differences, or residuals (actual seeded rainfall minus predicted unseeded rainfall), for the seed days and by a comparison of these residuals with the residuals for the random control days. We estimated and analyzed "bias effects" by means of a comparison of the covariates or predictors on seed and random control days. In this way, we determined whether the seed days were naturally disposed to be wetter or drier in the mean than the controls.

Table 4 summarizes the results from five of the predictor models. Column 2 gives the predictor equations as determined by the stepwise regression technique. These equations are empirical relations based on the use of random control data. Column 3 is the square of the correlation between the covariates and the actual rainfalls on the control days. Columns 4 through 6 give the basic statistics (sample size, sample mean, and sample variance) for the control residuals (actual rainfall minus predicted rainfall). Columns 7 through 9 give the basic statistics for the seeded residuals. These can be interpreted as the "seeding effects" appropriate for the model in question. Each residual is the actual (seeded) rainfall minus the rainfall the predictor model says would have occurred had there been no seeding. For the category 1 models there are two sets of data. The first set was calculated with the very disturbed seed day, 22 June 1975, excluded; the second set includes that day. Column 10 tests the seeded versus control residuals for equality of means (Welch test), and column 11 tests the seeded versus control residuals for equality of variances (F test). The variance tests are two-tailed, the means test one-tailed. Columns 12 through 17 give the basic statistics for the predictors themselves. Columns 18 and 19 give the results of testing the predictors for equality of means and variances. We used the same tests for the predictors as were used to look for seeding effects in the residuals, except that in this case the means tests are two-tailed.

The covariate analysis (Table 4) produced the most significant results in terms of probability levels (P_α) for seeding effects. The predictor equations provide an excellent fit to the control data, as evidenced by the high values of the square of the correlation between the predictors and the actual rainfalls and the small values of the control residuals. In category 1 the mean seed residuals are large and statistically significant at the 5 percent level in both the floating and total targets, suggesting a positive effect of seeding. If we assume that an estimate of the magnitude of the effect of seeding is provided by the ratio of the seed residuals to the mean predicted seed rainfall, the suggested effect exceeds 50 percent for both the floating and total targets.

The situation in category 2 is more complicated, probably as a result of the much smaller total sample. For the floating target the mean seed residual is large, positive, and nearly significant, but in the total target the mean seed residual is

Table 4. Summary of predictor models and results (rainfall units are cubic meters × 10^7). Abbreviations: $\hat{R}$, rainfall predicted from control of the correlation between the predictor and the actual rainfall on control days; N, number of days; x (residual), actual rainfall minus predicted

Descriptions of response variable	Predictor equation for control rainfall	r^2	Basic statistics on the residuals: Control residuals			Seeded residuals			P_α levels for seeding effects	
			N	$\bar{x}$	s^2	N	$\bar{x}$	s^2	Means	Variances
Echo motion: *TT*	$\hat{R} = 1.367 + 0.102c + 7.817p$	0.63	14	0.0000	2.8426	19 20	1.7626 1.2811	13.1719 17.1150	0.041 0.1182	0.0037 0.0010
Echo motion: *FT*	$\hat{R} = -0.199 + 0.128c + 6.352p$	0.66	14	0.0000	1.9223	19 20	1.6205 1.1805	8.7245 12.1377	0.026 0.097	0.004 7.26×10^{-4}
No echo motion: *TT*	$\hat{R} = 13.4882 - 2.6928c + 0.2149c^2 - 0.6929N_e^2$	0.92	8	0.0325	1.1129	6	−0.0717	29.5633	0.4839	5.04×10^{-4}
No echo motion: *FT*	$\hat{R} = 3.3384 - 0.7002c + 0.1104c^2 - 0.9919N_e^2$	0.83	8	0.0175	2.6611	6	2.9417	14.2380	0.0774	0.0323
No echo motion: *NFT*	$\hat{R} = 8.7511 - 2.1366c + 0.1170c^2 + 0.2205S^2$	0.92	8	0.118	0.6671	6	−4.4000	10.3204	0.0149	0.0023
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)

near zero. In view of these results, it is hardly surprising that the mean seed residual for the nonfloating target is large and negative. These results suggest that seeding increased the rainfall in the floating target but decreased it in the nonfloating target, accounting for the near zero effect in the total target. If real, this result suggests that the rain decreases in the area surrounding the invigorated seeded complexes on days when there is no echo motion. However, because the sample size is so small, these results cannot be interpreted as conclusive.

An examination of the basic statistics on the predictor models themselves provides some evidence that the seed days were disposed to be drier than the controls. Although this is not a conclusive result as evidenced by the P_α levels for bias effects, it does suggest that the effect of seeding as determined without covariates (Tables 2 and 3) has been underestimated.

Bases and History of the Echo Motion Covariate and Predictors

Although echo motion category was not explicitly identified as an important covariate until after the FACE 1973 experiment (*3*), the inverse relation between air motion over an island heat source and cumulus development has been known for over 20 years and can also be derived from hydrodynamic and thermodynamic equations (*9*). The results that emerge from both theory and observations of small islands are that, when the wind is light, a region (or regions) of convergence appears over the heated landmass, which results in showering cumuli. On days when the wind is strong, no region of convergence appears; the cumuli are suppressed and there is little or no rain. Pielke (*10*) has shown that, although certainly an oversimplification, this general picture applies to the Florida peninsula as well. On the basis of these observations, it is not at all surprising that, in the absence of disturbances, experimentation days with light winds tend to be wetter than days on which the winds are stronger.

According to statisticians, most of the key results derived so far from FACE are only as sound and reproducible as the predictors and the echo motion covariate. Of the four predictors used in this analysis, only seedability is derivable from a dynamic model. Nevertheless, all were defined and used as covariates either prior to or beginning from the original design of FACE. Prewetness, echo coverage, and earliness were used as covariates or predictors, or both, in the Florida randomized single-cloud experiments of 1968 through 1970 (*1*). In these experiments, prewetness, defined as the rain from the cloud for the 10 minutes prior to the seeding run, was found to be a significant predictor for the control cloud rainfall. Echo coverage was found to contribute only a negligible further reduction in variance for the control single clouds. In the single-cloud experiments, model-predicted seedability was found to correlate with seeding effect on cloud height and with the increment in rainfall from the seeded clouds relative to the controls.

After FACE 1973, an intensive effort to use prewetness, echo coverage, and a one-dimensional model output called M, or unseeded precipitation production, as predictors for unseeded rainfall was undertaken. Although some marginally significant regressions were obtained, the effort failed largely because it occurred prior to the recognition of the importance of the category of echo motion.

Echo coverage and earliness were used as stratification variables with dynamic seeding in Florida as far back as the original design of FACE in 1970 or earlier. They were empirically recognized as associated with heavy rainfall, since they were used in an effort to screen out naturally rainy days from the experimental sample. The single-cloud results suggested a lessened effect of dynamic seeding in Florida on naturally disturbed or rainy days. In 1968, a disturbed day was defined as a day on which echo coverage exceeded 13 percent (*1*). The subtraction of earliness from seedability in the aircraft launch criterion represents an effort to avoid experimentation on disturbed days.

Of the four predictors, then, the relationship of earliness, echo coverage, and prewetness to unseeded rainfall was either known or suspected for a long time. Only seedability is used here for the first time as a predictor of unseeded rainfall; it ranks low in the hierarchy.

Supportive Evidence

Validity of radar evaluation of rainfall. Radar is being used increasingly for the estimation of rainfall, even though rain gages are still the accepted standard. Woodley *et al.* (*6*) have painstakingly compared rain gages and radar for the estimation of areal precipitation, concluding that radar estimates of rainfall after adjustment by rain gages dispersed in small, discrete arrays are superior to rain gage estimates alone in many circumstances. Nevertheless, additional analyses supportive of radar estimation of rainfall are desirable whenever possible.

Rain gages have been dispersed in arrays of varying size within the FACE target since 1973 for use in the adjustment of the radar estimates of rainfall (see Fig. 1). In all instances these gages were too few in number and too localized to be acceptable for evaluation of the FACE experiments. Nevertheless, these gage measurements should at least be supportive of the findings based on radar evaluation.

At the suggestion of Flueck (*11*), we analyzed and examined rain gage measurements of rainfall from experimental clouds during 1973 and 1975 for con-

equation; $\bar{\hat{R}}_{NS}$, mean predicted control rainfall; $\bar{\hat{R}}_S$, mean predicted seed rainfall; r^2, the square rainfall; s^2, sample variance.

Basic statistics on the predictors							
Control predictors			Seed predictors			P_α levels for bias effects	
N	R_{NS}	s^2	N	$\hat{R}_S$	s^2	Means	Variances
14	4.629	3.761	19 20	3.608 4.117	2.873 7.905	0.1396 0.5464	0.3147 0.0885
14	2.5850	3.6489	19 20	1.4858 2.0465	2.5116 8.6675	0.102 0.535	0.228 5.66×10^{-2}
8	8.9188	12.1362	6	7.7617	9.5270	0.5554	0.4042
8	4.1675	12.5090	6	2.5000	0.6583	0.2631	2.69×10^{-3}
8	4.7475	7.4891	6	6.6483	10.0696	0.3045	0.3603
(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)

Table 5. Mean rain intensities by pass; *N*, number of samples.

Year	Stratification	*N*	Initial rain rate (mm/hour)	Change in rain rate (mm/hour)*
1973	Seed, motion	167	2.5	20.8
1973	Control, motion	48	1.9	8.9
1973	Seed, no motion	17	2.5	21.8
1973	Control, no motion	59	2.5	8.1
1973	Seed, all samples	184	2.5	20.8
1973	Control, all samples	107	2.2	8.4
1975	Seed, motion	196	2.2	17.8
1975	Control, motion	104	2.7	22.4
1975	Seed, no motion	85	2.5	19.8
1975	Control, no motion	66	2.0	26.7
1975	Seed, all samples	281	2.3	18.3
1975	Control, all samples	170	2.3	24.1
1973 and 1975	Seed, motion	363	2.3	19.3
1973 and 1975	Control, motion	152	2.5	18.3
1973 and 1975	Seed, no motion	102	2.5	20.1
1973 and 1975	Control, no motion	125	2.3	18.0
1973 and 1975	Seed, all samples	468	2.4	19.3
1973 and 1975	Control, all samples	276	2.3	18.0

*Within 30 minutes of the seeding pass.

sistency with the radar estimates of rainfall for the floating target. Of course, exact comparability could not be expected because the radar was used to determine total rain volume for target echoes, whereas the rain gage arrays could only sample rainfall from random portions of these echoes. In fact, the chance sampling of the rainfall from experimental clouds by rain gages made us skeptical that this exercise would be worthwhile.

We investigated the validity of the radar estimates of the effect of seeding in the floating target. Radar observations were used to determine when floating target echoes were over the rain gage arrays. In this determination, those portions of the rain gage records corresponding to rainfall from experimental clouds were analyzed. Portions of the rain gage records without rain, despite the radar indications that some rain should have occurred, were recorded as zeros. Days on which by chance no experimental echoes passed over gages, were not included. We were surprised to find that the ratios of seed to control floating target rainfall obtained with rain gages were larger by nearly a mean factor of 2 than those obtained by radar. This result certainly supports the positive results obtained by radar for the floating target and, if anything, suggests that the radar estimates of the seeding effect may be underestimates. A more quantitative statement is not possible because of the chance sampling of the experimental echoes by the rain gages. Although this analysis does support the positive result for the floating target, it cannot be construed as proof of the efficacy of dynamic seeding until questions of bias in the selection of the floating target have been answered.

Rain intensity from subject clouds. We studied the rain intensities (amount of rain per unit time) from subject clouds during FACE 1973 and 1975 to determine (i) whether the selection of clouds for the floating target might be biased because of the ability of observers to recognize when seeding is taking place (FACE scientists are sometimes able to recognize when seeding is taking place on the basis of cloud response) and (ii) whether seeded clouds produce heavier rainfall than control clouds. If the selection of experimental clouds was biased on the basis of early recognition of observers of whether or not seeding is taking place, one would expect seeded clouds to be more vigorous than the control clouds upon selection. Scientists investigated this possibility by examining the rain intensity in the experimental clouds at the time that the initial seeding took place. This study was done by two individuals who did not know the seed decision. The filmed radar observations of echoes contoured by rain intensity were examined for the GO days in 1973 and 1975. Five days out of the 36 GO days (9 August 1973, 9 and 16 July 1975, and 16 and 25 August 1975) were not used because the filmed radar data were either of poor quality or unavailable altogether. The digitized radar observations were not used because the computer output could not be made available in an appropriate time frame. No gage adjustments were applied to the filmed radar observations. This is not a problem because any errors should be random and effectively balanced out by the large data sample.

For every seeding pass of the aircraft, a rain intensity value is read from the film. Totals of 468 initial pass values of rain intensity on 18 seed days and 276 pass values on 13 control days were obtained. The number of seeding passes on control days is equivalent to 380 when normalized to 18 experimentation days, which suggests that there were more seeding passes (468 versus 380) on actual seed days than on control days. Some might consider this as evidence for bias, but we believe that on seed days more seeding opportunities are generated by virtue of the invigoration of the subject clouds that occurs as a direct result of the seeding.

The examination of the initial rain intensity in the area that was seeded in the subject clouds revealed no differences between the seed and control clouds in 1973 and in 1975. The mean initial rain intensities (Table 5) for seeded and control clouds in 1973 were 2.5 and 2.2 millimeters, respectively, and in 1975 they were 2.3 and 2.3 millimeters, respectively. This result suggests that there has been no systematic bias in the selection of subject clouds, even though it is sometimes possible to recognize when seeding is actually taking place. This finding greatly strengthens our interpretation that the greater rainfall in the floating target on seed days is real and not the result of conscious or subconscious bias.

An obvious extension of the rain intensity study is to determine whether there is any appreciable difference in the rain intensity after the seeding pass as a function of the seed decision. Because the seeded clouds grow larger, last longer, and produce more rainfall than the unseeded clouds, one might suspect that the rain intensity subsequent to the first seeding pass is greater in seeded clouds than in the controls. Earlier studies during the single-cloud experiments of 1968 and 1970 failed to reveal a significant difference in rain intensity between seeded and control clouds.

For every seeding pass made through the experimental clouds during 1973 and 1975 for which there were filmed radar data (468 seeding passes and 276 control passes), the rain intensity at the time of the pass and the maximum rain rate for 30 minutes after the seeding at the position of the seeding were calculated. In most instances the changes were positive; that is, it rained more heavily after real or simulated seeding than at the time of seeding. Mean rain intensity differences by pass were then stratified as a function of the seed decision, year (1973 versus 1975), and with echo motion or no echo motion.

Examination of the results (Table 5) suggests only a small overall effect of seeding on rain intensity. Furthermore, the results are not consistent from 1973 to 1975. The data for 1973 suggest a substantial mean increase in rain intensity associated with seeding, but the data for 1975 indicate a modest mean decrease in rain intensity associated with seeding. For both years combined, the mean result is a 7 percent increase in rain intensity associated with seeding. However, the lack of consistency in the results from 1973 and 1975 suggests that one can have little confidence in the overall result. There is presently no persuasive evidence that seeding had a pronounced effect on rain intensity.

These results appear to substantiate our earlier findings that the effect of dynamic seeding on rain intensity is small and secondary to its effect on cloud size and duration. Alteration of cloud size and duration must therefore account for most of the change in volumetric rain output from the seeded clouds.

Dynamic seeding and microphysical processes within Florida cumuli. For dynamic seeding to be effective, two microphysical requirements must be satisfied: (i) Florida convective clouds must contain appreciable quantities of supercooled water in their active updraft regions, and (ii) massive seeding with silver iodide must convert a substantial fraction of this supercooled water into ice in order that there be an impulsive release of fusion heat before the tower containing the supercooled water begins to decay.

Recent work has provided a better picture of microphysical processes in supercooled Florida cumuli and their alteration by seeding. Aircraft penetrations of clouds at the isotherm levels from −4° to −10°C have indicated that supercooled Florida cumuli can contain appreciable quantities (the order of ten crystals per liter) of natural ice, particularly in the inactive portions of the cloud. Even the supercooled water in the active regions of these cumuli begins to glaciate rather rapidly when the updraft begins to decay. The rapid glaciation of Florida cumuli appears to be related to a secondary mechanism for ice crystal production associated with the occurrence of raindrops (*12*) within the decaying updraft.

Because of the natural tendency of Florida cumuli to glaciate, dynamic seeding has a narrow "window" in time within which it can work effectively. The seeding agent must be delivered to the actively growing portion of the cloud when most of the hydrometeors are liquid, cloud-sized (diameter < 100 micrometers) droplets. Under these circumstances the impulsive increase in cloud buoyancy acts to invigorate the cloud before it begins to decay and natural glaciation processes become operative. Seeding outside this seeding window will invariably result in failure. Aircraft delivery of the seeding agent near the supercooled cloud tops is the only reliable technique for dynamic seeding in clouds with very warm (20°C) bases such as are found in Florida.

We now have evidence that dynamic seeding has been effective in glaciating a fraction of the supercooled water within the active updraft. This process normally does not occur naturally. Analysis of Formvar replicas of cloud particles obtained during FACE 1975 indicates that seeding produces large quantities of ice at a temperature of −10°C in actively growing clouds (*13*). This vapor-grown ice has a columnar habit with dimensions of roughly 45 by 150 micrometers, a size apparently too small for detection by an optical ice particle counter as configured for FACE 1975. This inability to detect such small ice particles certainly contributed to the earlier inconclusive findings by Sax (*14*), relating seeding to changes in ice particle concentration as measured with the ice particle counter. The sudden production of large quantities of vapor-grown crystals appears to be a seeding signature that currently can only be detected with the use of an impaction-type device, for example, a Formvar replicator.

The detection of microphysical changes in the cloud produced by seeding is of utmost importance because such changes are the first link in the chain of reasoning behind the FACE experiment (*2*). Prior to FACE 1975, we had documented seeding-induced changes in cloud dynamics and rainfall but we were unable to observe any changes in the microphysical structure of clouds due to the seeding. Without such measurements, the documented alterations in cloud dynamics were isolated from any direct observation of cause and effect.

Validity of the Z-R *relationships for showers from seeded clouds.* Rainfall estimates in FACE have been accomplished by converting radar observations of reflectivity to rainfall rate by means of the Miami reflectivity-rainfall rate (*Z-R*) relationship (*15*) (the radar estimates of rainfall are then adjusted with rain gages). A potential source of error in the radar estimation of rainfall, which is presumably accounted for by the rain gage adjustments in any case, is spurious reflectivities that occur as a result of a seeding-induced change in the drop size spectrum. Cunning (*16*) has investigated this possibility by comparing the *Z-R* relationships for showers from seeded and unseeded experimental clouds obtained during FACE. Using aircraft measurements of raindrop sizes at cloud base, Cunning found no differences in the intercepts or coefficients of the seed and the control *Z-R* equations at the 5 percent levels of significance. Furthermore, the actual differences between the seed and control data sets were small as compared to the natural inter- and intraday variability. Therefore, present evidence suggests that the drop size distribution at cloud base and hence the *Z-R* relationships are not affected by dynamic seeding.

This result is not altogether surprising, because the main apparent effect of seeding is an increase in the sizes and lifetimes and consequently in the amount of rainfall from experimental clouds. Although seeding may change the drop size distribution in the upper seeded region of the clouds, natural processes at work in the 6-kilometer distance between cloud base and the level of seeding apparently readjust the distribution so that differences are no longer detectable at cloud base.

Conclusions and Future Outlook

Conservatively, FACE 1970–1975 can be said to have achieved several significant results only in the data analysis sense and not in the sense of population inference. However, the results cannot be generalized outside of Florida, nor can complete confidence be placed in their replication even in Florida.

Significance could be claimed in the population inference sense if the echo motion covariate and predictors had been defined and established in the original design of the experiment, an impossible requirement; or if they could have been derived from physical principles. We believe that the sound derivation of the echo motion covariate places the results presented here a strong first step along the path between data analysis and population inference. Nevertheless, cautious optimism should be applied, particularly to estimated magnitudes of seeding effects and to any statements regarding category 2, in view of the small sample.

One conclusion that seems strongly supported by the rainfall results is:

1) Echo motion category is of predominant importance in accounting for rain variations in both floating and total targets. It accounts for more of the rainfall variability on experimental days than treatment, year, or any other single variable discovered so far. Our strongest conclusion is that the FACE data must be analyzed with echo motion category in mind. Although this conclusion cannot necessarily be extrapolated to dynamic seeding experiments outside of south Florida, the probability is high that it will remain a key covariate in replications of FACE.

The remaining conclusions are considerably more tentative:

2) For category 1, moving echo days (basis: 20 random seed and 14 random control days), both floating target and total target rainfalls indicate a positive significant treatment effect; seeding increases the variance significantly in both floating and total targets, suggesting negative effects on some days and positive effects on others; the best rough estimate of the magnitude of the mean seeding effect is about 60 percent for floating target and 25 to 35 percent for total target rainfalls; and these results could be conservative as there is some evidence (from the predictor models) of negative bias, that is, naturally drier seed days.

3) For category 2, stationary echo days (basis: six seed and eight control days), floating target rainfalls indicate a positive significant treatment effect; total target rainfalls indicate no significant treatment effect; nonfloating target rainfalls indicate a significant negative treatment effect; there is a significant increase in the variance of both floating and total targets caused by treatment; rough magnitude estimates are an increase of 50 percent or more in floating target rainfall, with an even larger percentage decrease in nonfloating target rainfall; and there is some evidence, from the predictors, of negative bias, that is, naturally drier seed days.

The apparent compensation (localized increases in rainfall caused by seeding result in compensatory decreases in rainfall elsewhere) on category 2 days appears puzzling; it occurs in a very small sample. Nevertheless, if confirmed by further experimentation, it does have a plausible explanation. When cumuli are moving, they can usually keep feeding on fresh subcloud air. On the other hand, when clouds grow and die in the same location, penetrative precipitating downdrafts stabilize and dry the lower boundary layer, limiting the supply of fresh subcloud air for new growth. Since the "robbing Peter to pay Paul" uncertainty is one of the major questions in rain augmentation experiments, it is urgent that this point be investigated from the practical as well as the scientific viewpoint.

Although much progress has been made, it is clearly premature to try to translate the results of FACE into any operational program. On the other hand, many of the concepts and procedures of FACE might be usefully applied to randomized dynamic seeding experiments planned elsewhere such as in the U.S. high plains and in South Africa. The identification of covariates and the multipurpose use of models, for both single clouds and the mesoscale, may prove valuable in combining the physical design with the statistical design and analyses.

Summary

The latest rainfall results of the Florida Area Cumulus Experiment (FACE) are discussed after a review of the background, design, and early results of this experiment. Analysis without the benefit of data stratification and appropriate covariates of the 48 random experimentation days obtained through 1975 provided no evidence that dynamic seeding appreciably altered the rainfall over the fixed target area (1.3×10^4 square kilometers). Partitioning of the experimentation days according to whether the convective echoes moved across the Florida peninsula or developed in situ was more informative. Use of this echo motion covariate with five meaningful predictor models of natural rainfall in a stepwise regression program produced persuasive evidence for an effect of seeding in both echo motion categories. For days with moving echoes, there is evidence for a positive, statistically significant treatment effect on the rainfall from the subject clouds (the floating target) and in the overall target area. The results for days with stationary echoes, although considerably more tentative, suggest that seeding produces more rainfall in the floating target but with no net change of the precipitation in the overall target area. The ramifications of this result and a possible explanation are discussed. Corroborative statistical analyses and discussion are presented, including a discussion of the physical bases and history of the echo motion covariate and the meteorological predictors, analysis that is supportive of the rain-gage-adjusted radar measurements of precipitation in FACE and results of relevant cloud physics measurements in Florida.

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