Florida Area Cumulus Experiments 1970–1973 Rainfall Results

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ABSTRACT

After four summer periods of randomized experimentation with dynamic cumulus seeding in a 1.3×10^4 km^2 target area in south Florida, 14 seed and 23 control cases are available, with increased documentation of radar measurement accuracy.

Seed-control rainfall comparisons are made for "floating" and total target for the 6 h period following the first seeding. On days screened as suitable for the experiments, natural rain volume varied by a factor of 62 for floating target and by a factor of 25 for total target. Area seed-control rainfall differences are not significant with six classical tests, nor is the difference between random and non-random controls.

Analysis of isolated experimental clouds obtained on days of multiple cloud seeding produced significant findings. Results were stratified depending on whether the single clouds dissipated in the target area without merger or whether they merged with a neighbor. With the former stratification, the mean seeded rainfall exceeded the mean control rainfall by a factor of 2, a result (one-tailed significance of 3%) that is consistent with earlier single cloud studies. No meaningful rainfall comparison was possible with the latter stratification because, on the average, the seeded clouds merged (and were dropped) 13 min earlier than the controls. This disparity in mean lifetimes before merger (two-tailed significance level of 0.5%) suggests that seeding is promoting merger in FACE as intended.

Several Bayesian approaches are used to estimate a probability distribution of a multiplicative seeding factor, based on gamma rainfall distributions, with the same shape parameter for seeded and control populations. The most general treatment assigns prior probabilities to three variables, the common shape parameters, the mean of the control distribution, and the multiplicative seeding factor. With existing data, 95% of the area under the marginal density of the seeding factor lies between about 0.7 and 1.7, with a mean just above and a mode just below 1.

After extensive search for physically meaningful covariates or predictors, radar echo motions in or near the target related to two distinct rainfall populations. Category 1 comprised those cases where echoes were "marching" across the area. Category 2 comprised those cases with growth and dissipation virtually without motion. Echo motion is shown to be a statistically significant covariate, accounting for 30% of the variation in the total rainfall. For the afternoon measurement period, the mean target rainfall in Category 2 cases exceeded that in Category 1 cases by a factor of 2.5.

Separate seed-control comparisons in the two categories indicate that different effects of seeding might be sought in continued experimentation. Although the existing sample is small, there is evidence that in Category 1 (marching) the seeding effect is probably not multiplicative.

Attempts are in progress to estimate the number of further cases required to resolve a range of postulated seeding effects in this experimental context.

1. Introduction

In September 1973, the fourth summer experimentation period was completed comprising randomized dynamic cumulus seeding in a 1.3×10^4 km^2 target area in south Florida (Fig. 1). The design, physical background, execution and early results of this experiment have been described in the literature (Simpson and Woodley, 1971; Simpson *et al.*, 1973a).

On suitable days, neighboring cumuli are seeded massively with airborne silver iodide pyrotechnic flares (100–1000 g per cloud) with the aim of inducing enhanced growth and merger of two or more clouds. The motivation of the experimental series is to determine whether and under what conditions rainfall can be increased by dynamic seeding and also to improve understanding of and ability to simulate cumulus processes and interactions.

Radar-evaluated rainfall is compared for both floating targets and in the total target. The floating target com-

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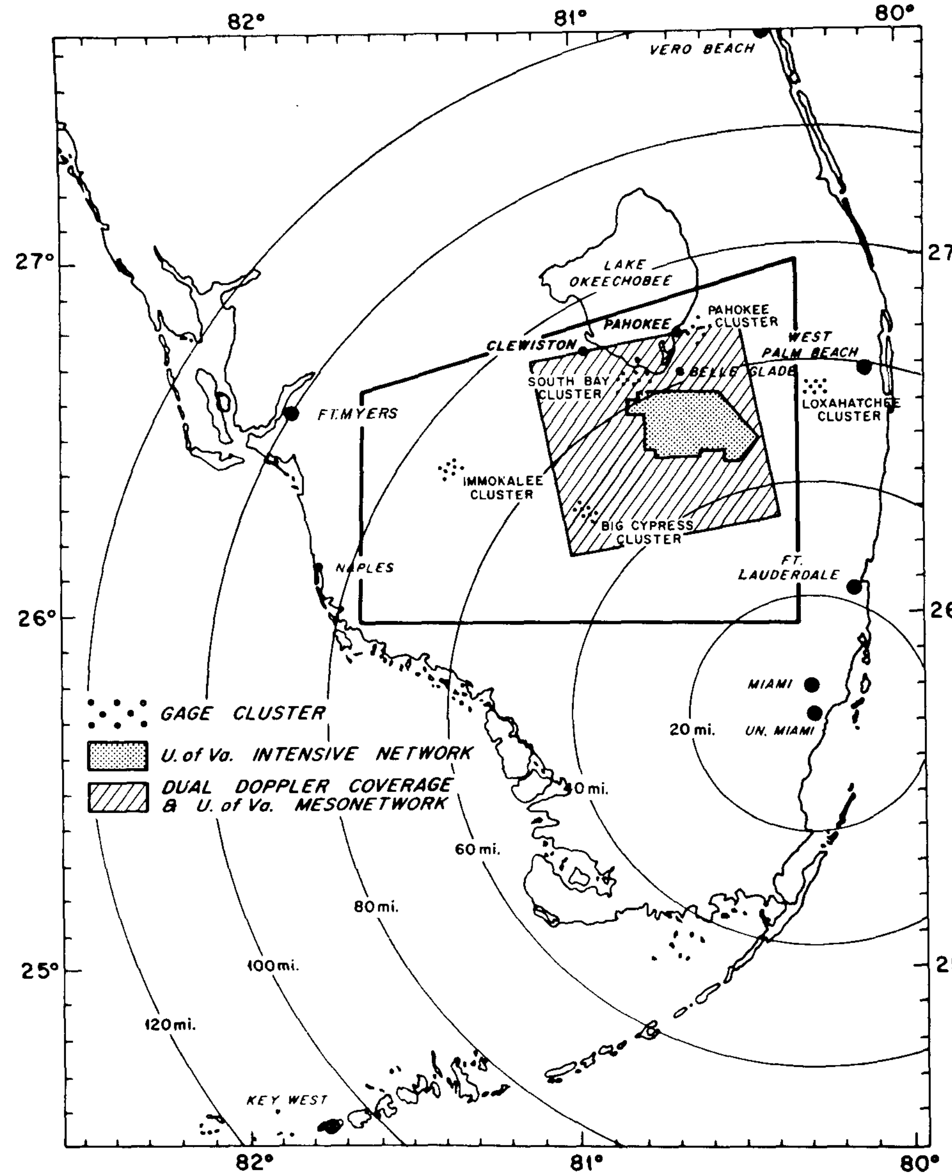

FIG. 1. Field design for FACE experiments. The largest quadrilateral is the EML target.

prises all radar echoes undergoing a "seeding" pass by the aircraft and all those other echoes merging with them so long as the echoes or complex remain within the total target. Up through 1972, there existed seven random seed cases, five random controls, and six non-random controls. Seed-control differences were positive, with a 10% significance level for the floating target and no significance for the total target.

In the summer of 1973, a longer and more intensive experiment was undertaken called FACE (Florida Area Cumulus Experiment) 1973, running 94 days from 11 June through 12 September, inclusive. The tools included four aircraft, dense surface networks, an operational 10 cm radar digitized and calibrated for rain measurement, a dual Doppler radar for research, quantitative time-lapse photography from the ground and air, and chemical rain sampling.

Objectives were divided into a core program and 14 sub-programs (Staff, EML, 1974) several of which are described in this issue (Woodley *et al.*, 1975; Olsen and Woodley, 1975) and elsewhere.[2]

This paper describes the results of the core program to date, namely the comparison of seeded and control rainfalls and procedures to deduce seeding effects.

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[2] See contributions by Cotton and Boulanger (1974) and Lhermitte and Sax (1974) in Preprint Volume, Fourth Conference on Weather Modification, American Meteorological Society.

TABLE 1. Operational results FACE 1973.

- 94 days available (11 June–12 September, inclusive)
  - 19 qualified for experiment (20%)
    - 12 random GO days
      - 7 seed and 5 control
    - 7 non-random control (light aircraft)
- 75 total days rejected as unsuitable
  - 18 days rejected in air (19%)
    - 10 too wet and/or disturbed
    - 8 days insufficient suitable clouds
  - 57 days rejected without flying (61%)
    - 3 because of possible severe weather
    - 3 too dry
    - 51 too wet and/or disturbed

2. The 1973 seeding program and rainfall data

Table 1 summarizes operational results for FACE 1973.

In the target area, the summer of 1973 was much wetter than previous years of experimentation, accounting for the fact that only 20% of the days, rather than the usual 33%, qualified for the experiment. Days were usually rejected prior to flight if they met the criterion that $S-N_e<1.5$, where S is dynamic seedability (km) defined by the EML one-dimensional model (Simpson and Wiggert, 1969, 1971) and N_e is the number of hours between 1000 and 1200 EDT in which one or more echoes occur in the target. Days were rejected in flight if fewer than six seedable clouds could be found in the target (or fewer than 60 flares expended); this type of rejection occurred eight times, nearly all on dry days.

TABLE 2. FACE 1973 rainfall results. Units 10^7 m^3.

Date	Action†	$S-N_e$	Echo coverage (percent)	Floating target rainfall volume	Total target rainfall volume	Category
June 26	RC	2.25	1	3.37	5.90	1
July 7	S	2.00	3	1.80	3.17	2
July 9	RC	2.60	1	3.67	6.59	2
July 16	NS	3.30	5	2.20	4.79	2
July 17	NS	2.60	3	1.93	4.42	1
July 20	S	1.90	4	7.93	10.04	1
July 25	S	3.40	2	0.95	1.63	1
July 26	RC	3.75	2	1.91	3.99	2
Aug. 6	NS	1.95*	1	5.80	12.13	2
Aug. 9	NS	1.60	23	2.67	3.54	1
Aug. 11	RC	3.95	1	1.87	2.27	1
Aug. 14	RC	2.85	3	7.41	10.40	2
Aug. 22	S	2.85	~0	3.19	4.13	1
Aug. 25	S	1.80	3	3.47	5.45	1
Aug. 26	RC	0.80*	1	2.14	5.86	1
Aug. 27	S	2.40	2	0.37	0.83	1
Aug. 28	S	5.05	3	0.32	1.12	1
Sept. 9	NS	3.55	1	0.16	0.48	1
Sept. 10	RC	M	M	1.02	1.48	1

† RC, non-random control; NS, random control.
* Value doubtful.

TABLE 3. FACE 1970–72 rainfall results.

Date	Action	$S-N_e$	Echo coverage (percent)	Floating target	Total target	Category
1970						
June 29	S	3.00	3	0.20	3.97	1
June 30	NS	1.10	13	3.79	8.55	2
July 2	S	5.00	2	1.37	2.39	2
July 7	NS	3.20	2	0.96	9.26	2
July 8	S	3.90	4	12.13	14.64	2
July 17	RC	2.80	2	—	5.74	2
July 18	S	2.70	~0	5.61	10.36	2
1971						
June 16	S	2.40	~0	0.28	0.31	1
July 1	NS	1.70	2	0.32	1.94	1
July 12	NS	2.50	1	0.43	9.27	2
July 13	S	3.40	2	1.94	3.68	1
July 14	S	2.60	1	2.05	6.03	1
July 15	NS	2.40	3	1.18	2.31	1
July 16	RC	3.40	~0	1.23	8.61	2
1972						
July 21	RC	2.00	~0	0.12	0.27	1
Aug. 4	RC	1.35	~0	0.28	0.32	1
Aug. 9	RC	1.70	~0	2.64	3.74	1
Aug. 18	RC	1.30	~0	1.41	3.33	1

The method of rainfall evaluation has been described by Woodley *et al.*, (1975). Radar results for 1973 were adjusted using five gage clusters and comparing both adjusted and unadjusted values with the gage-measured rain in a dense micronet. Woodley *et al.* (1975) showed that unadjusted radar estimates of area-mean rainfall were as accurate as gage results with 1 gage per 25 mi^2, while cluster-adjusted radar estimates of area-mean rain were as good as those obtained with 1 gage per 10 mi^2 spread out over an area of 250 mi^2. They further showed, using the gamma function properties of the data (Olsen and Woodley, 1975), that the power of statistical tests is little reduced by the measurement errors relative to the problems created by the large variability and small sample size. Therefore, the rain results to be presented here will be treated as if they were error-free.

Table 2 presents the rainfall results for the 19 GO days of 1973. Results from the 18 GO days in 1970, 1971 and 1972 are shown in the same units in Table 3. The column marked "category" will be explained later in Section 5. There are now a total of 14 seed days, 23 controls (22 for floating target), of which 10 are random and 13 non-random[3] (12 for floating target).

There is some evidence that the radar data in 1970 and 1972 were as accurate as those tested carefully in 1973. Those in 1971 were certainly less accurate than

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[3] Non-random controls were flown in a light aircraft on days suitable for the experiment on which a seeder aircraft was unavailable. The flights were necessary to ensure that adequate numbers of seedable clouds were indeed present in the area, to select floating targets, and to simulate flare releases (Simpson *et al.*, 1973a).

in the other years. The best available gage adjustments have been made with these data.

From Tables 2 and 3 it is seen that on unseeded days selected as suitable for experiment, natural rainfall varied by a factor of 62 in the floating target and by a factor of 25 in the total target.

Table 4 presents the means and standard deviations for the rainfall figures of Tables 2 and 3, combining all experimental periods.

It is a noteworthy, but not new, result that in Table 4 the standard deviations are comparable to, and in some cases exceed, the mean rainfall values.

For the floating target, the overall seed-control ratio is 1.4, while it is 0.99 for the total target. These are *not* estimates of seeding factors, which will be attempted later. The seed-control differences in Table 4 are not significant by six classical tests[4], nor is the difference between random and non-random controls. A puzzling feature of Table 4 is that for floating targets, the non-random controls are 16% wetter than the random controls, while for the total target, the random controls are 26% wetter than the non-random controls. This could be either pure chance or unconscious bias on the part of the Project Director (the second author) in leaning over backward to select wet floating targets on non-random control days. Both alternatives are being examined.

When the 1973 results alone are considered, the seed-control ratios are 0.90 for floating target and 0.73 for total target. There are many possible explanations. Among them are six not mutually exclusive inferences:

1. Seeding had no effect and the differences are due to chance.
2. Seeding had no effect on the floating target and a negative effect on the non-floating (unseeded) clouds and cloud complexes.
3. Seeding was increasing the rain in the floating target at least, but the control days were naturally wetter.
4. Seeding was decreasing the rain in both targets in 1973.
5. Seeding may have had positive effects on some occasions and negative effects on other occasions, with more of the former cases in 1970–72 than in 1973.
6. Sample size is too small to infer anything concerning seeding effects owing to the very large natural variability.

The following analyses attempt to start the selection process between alternatives. Goals are to provide the best estimates of seeding effects that are possible with existing data and also to predict the extent of further experimentation necessary to resolve seeding effects of a reasonable range of magnitudes, with available information concerning the natural variability of the target rainfall and the physics of the clouds producing it.

TABLE 4. FACE rain results 1970–73: means and standard deviations. Units 10^7 m^3.

	Floating target			Total target		
	n	$\bar{R}$	σ	n	$\bar{R}$	σ
All seed	14	2.97	3.45	14	4.84	4.18
All control	22*	2.11	1.84	23	4.88	3.43
All fair controls**	20*	2.00	1.88	21	4.77	3.49
All random controls	10	1.94	1.78	10	5.67	3.87
All fair random controls**	8	1.62	1.84	8	5.57	4.17
All non-random controls	12*	2.25	1.95	13	4.50	3.07

* There was no floating target on 17 July 1970.

** Fair day defined as 1400 EDT echo coverage <13%.

3. Analysis of single clouds in FACE

The only statistically significant evidence to date which supports the seeding hypothesis comes from a study of single clouds in the area experiment. At the suggestion of Dr. A. Olsen, the rainfalls from all individual experimental clouds obtained on FACE days were calculated. A partial motivation was to determine whether the effect of dynamic seeding on individual clouds as documented by Simpson *et al.* (1971) was persisting in FACE. Of course, exact comparability was not expected because the motivation and experimental procedures were different in the two experiments. In the single cloud experiments of 1968 and 1970 only relatively isolated clouds were selected for experimentation, approximately 1 kg of silver iodide was expended in each cloud, and the aircraft stayed with each cloud until its demise. In the FACE program, clouds with merger potential were selected, a variable amount of silver iodide was expended in each cloud, and the seeder aircraft roamed from cloud to cloud with no set pattern. In both experiments, the subject clouds could easily be followed on radar.

Analysis procedures for FACE single clouds were the same as those described by Woodley (1970) for the single cloud experiments of 1968 and 1970. In all instances, the rain calculation was terminated when the experimental echo merged with a neighbor at the second contour above the minimum detectable signal. This analysis restriction is at odds with the intent of the FACE procedures which were to promote merger. Nevertheless, it was necessary to insure comparability with the single cloud studies of 1968 and 1970 to insure an objective determination of single cloud rainfall.

Detailed data were obtained from 276 single clouds (107 seeded and 169 unseeded) in the area experiment.

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[4] The tests used were Mann-Whitney-Wilcoxon, Squared-rank, Student-t (with fourth root and logarithmic transform), Optimal $C(\alpha)$, and Maximum Likelihood.

TABLE 5. Mean rainfalls (10^3 m^3) from single clouds in FACE.

Seeded clouds			All controls			
n	Lifetime (min)	$\bar{R}_v$	n	Lifetime (min)	$\bar{R}_v$	$\bar{R}_{vs}/\bar{R}_{vc}$
Dissipating without merger						
59	38.9	384.5	87	36.7	194.1	1.98*
Merging clouds						
48	27.0	329.7	82	40.3	377.2	**

* This result significant at 3% level.

** This ratio is meaningless because of disparity in mean lifetimes. The 13 min mean difference in lifetime before merger is significant at the 0.5% level.

These were subdivided into several stratifications, in particular "dissipate without merger" or "merge." Those clouds in the former category are most comparable to the single clouds of 1968 and 1970. Results are presented in Table 5.

For FACE single clouds that existed without merging, the ratio of mean seed to control rainfall is near 2 (one-tailed significance level of 3% with Student-*t* test applied to the logarithms of the rainfalls), in excellent agreement with the original single cloud studies that indicated a seeding effect of between 2 and 3. The overall single cloud sample size is now nearly four times what it was prior to this study.

Examination of the results for FACE single clouds that merged reveals a much diminished effect of seeding. This is puzzling at first, until one notices the mean lifetime of the single clouds before merger, which was 27 min for the seeded clouds, and approximately 40 min for the controls. Consequently, the apparent seeding effect is smaller for this category, because on the average the seeded single clouds merged (and were dropped) 13 min earlier than the controls. Therefore, a meaningful comparison of rainfalls of merging clouds is not possible.

The disparity in mean seeded and control cloud lifetimes before merger is an important finding. The lifetimes were well fitted by the log-normal distribution, so that the Student-*t* test could be applied to their logarithms. With that test, the seed-no seed difference in time to merger is significant at the $p=0.005$ level with a two-tailed test. The more rapid merger of seeded clouds on seed days is encouraging, since one of the goals of the experiment is to promote merger by seeding.

TABLE 6. FACE 1970–73 rainfall data using best fit gamma function parameters.*

	Shape α	Scale β
Floating target		
Control	1.25	0.590
Seed	0.88	0.296
All	1.04	0.427
Total target		
Control	1.49	0.298
Seed	1.33	0.275
All	1.42	0.288

* R in units of 10^7 m^3.

The single cloud analysis of FACE clouds was informative. It demonstrated that dynamic seeding is continuing to produce more rainfall from single clouds and that seeded clouds are merging more rapidly than control clouds as intended. It is still not known whether these effects will manifest themselves as more rainfall in the target area.

4. Seeding factor estimates for FACE without covariates or data stratification

Earlier EML studies (Simpson, 1972: Simpson *et al.* 1973a) suggested that Florida convective rainfall data are adequately fitted by gamma distributions of the form

$$p(R)=\frac{\beta^{\alpha}}{\Gamma(\alpha)}R^{\alpha-1}e^{-\beta R}, \tag{1}$$

where the shape parameter α varied little between seed and control populations, which differed only in the scale parameter β.

The increased area data sample of 14 seed and 23 (22 for floating target) control cases permits improved assessment of distributions. With maximum entropy (Tribus, 1969; Simpson and Pezier, 1971) and the χ^2 test, the gamma was found to be a good to excellent fit to all data subsets, except the total target control, where it was only fair. Table 6 gives the best fit parameters for (1).

The difference between seed and control values of α for the floating target is not significant, since the fractional variance for that sample size is about 0.25 when α is in the range 0.8 to 1 (Bowman and Shenton, 1970). Although the difference in α between floating and total target is not significant either, it amounts to nearly two standard deviations.

We define a multiplicative seeding factor F as follows:

$$F=\frac{\langle R_S\rangle}{\langle R_{NS}\rangle}, \tag{2}$$

where $\langle R\rangle=\alpha/\beta$ is the expected value of the distribution.

Here we conduct Bayesian analysis on three levels of sophistication, all assuming $\alpha_S=\alpha_{NS}$.

In the simplest example, we use Bayes equation in the form

$$p(F|D)=p(F)\frac{p(D|F)}{p(D)}, \tag{3}$$

following the procedure of Simpson *et al.* (1973a). Here D is the set of seeded data. We assume $\alpha=1$ for floating targets and $\alpha=1.44$ for the total target. The natural (unseeded) distribution is determined from the sample average of the control cases.

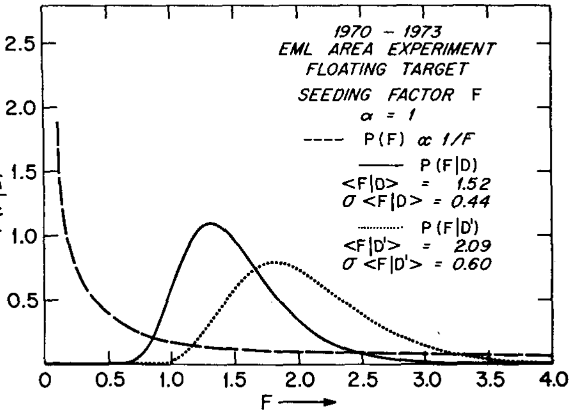

Fig. 2. Bayesian analysis for seeding factor F: dashed curve, prior on F proportional to $1/F$; solid curve, posterior probability of F with actual seeded data, set D; dotted curve, posterior probability of F with hypothetical seeded data, set D', obtained by switch of one wet and one dry day (see text).

Using the FACE 1970–73 data and two types of diffuse priors on F, we obtain the results shown in Figs. 2–5. Several other classes of priors have been tested, many very much more unfavorable, with no significant difference in the results. For floating targets, expected values of F are 1.52 and 1.63, with modal values of 1.31 and 1.41 for prior proportional to $1/F$ and modified uniform, respectively. The latter has equal area in the range below and above 1. In the former less favorable cases, equal-tailed 95% confidence limits on posterior F cover the range from 0.87 to 2.57. For the total target, expected values are 1.04 and 1.06, with modal values 0.94 and 0.90. The 95% equal-tailed confidence limits for posterior F are 0.67–1.69.

The sensitivity of results to the combined small sample and "heavy-tailed" rainfall distributions is illustrated by the dotted curves in Figs. 2–5. The dotted curves were obtained as follows: On 14 August 1973, the only available seeder aircraft was forced to abort. The authors went to great effort to fly a nonrandom control on that day, which proved to be the third wettest in the entire four-year sample, for both floating and total target. If the seeder had flown on that day, and the remainder of the randomized instructions had been executed in order, this would have changed wet 14 August 1973 from a control to a seed day, and dry 28 August 1973 from seed to control, leaving the remaining instructions unchanged. If none of the rainfall data were altered in the process, we would get the results for the posterior probability of F shown by the dotted curves in Figs. 2–5. These probability density distributions are not only considerably different from the solid curves, but ironically enough, the floating target seed-control "difference" is "significant" at 5% with the Maximum Likelihood and Optimal $C(\alpha)$ tests.[5]

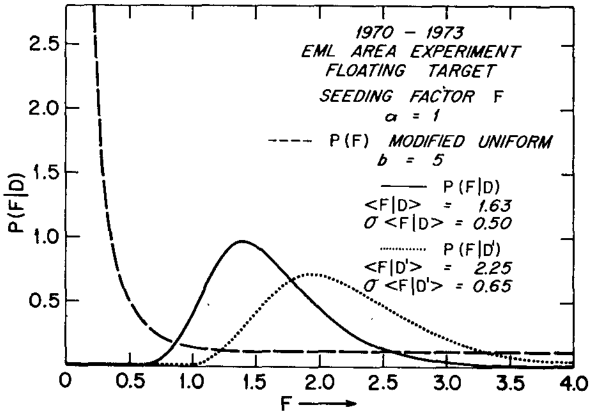

Fig. 3. As in Fig. 2 except with modified uniform prior probability on F. This distribution terminates at 5 and has equal area below and above 1.

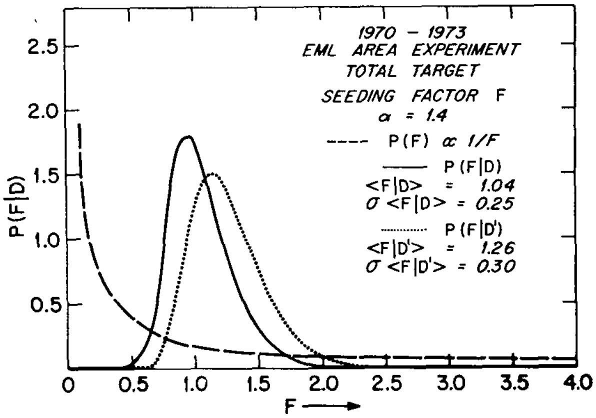

Fig. 4. As in Fig. 3 except for total target.

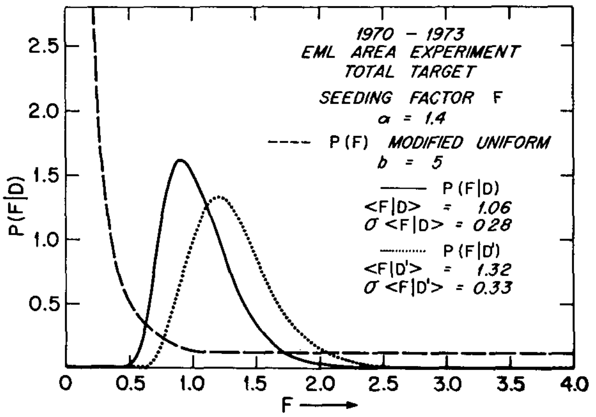

Fig. 5. As in Fig. 4 except with modified uniform prior on F, terminating at 5.

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[5] The difference is not significant at 5% with the non-parametric tests or with the t test (using the logarithm or fourth root of the data).

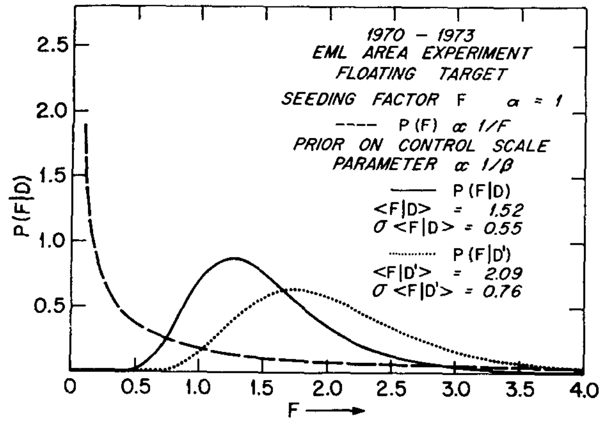

FIG. 6. Two-variable Bayesian analysis for seeding factor F for floating target. Joint prior on F (proportional to $1/F$) and control population scale factor β_c (proportional to $1/\beta_c$). Dashed line is prior F; solid line is posterior F with actual seeded and control data; and dotted line is posterior F with hypothetical data set, namely two days switched between seed and control (see text).

It is shown elsewhere in this issue (Simpson *et al.*, 1975) that heavy-tailed distributions like those from Florida convective showers are prone to this type of confusing result, even with considerably larger data samples than that currently available in FACE.

One of the greatest problems in assessing the seeding factor with the existing FACE data sample is uncertainty in determination of the natural rainfall distribution from the small number of control cases. Previous analyses (Simpson *et al.*, 1973b) showed from Monte Carlo experiments that a random selection of 20 cases from a gamma distribution with the shape parameter of concern here would give an $\bar{R}$ differing from $\langle R\rangle$ by 10% about 80% of the time, by 20% half the time, and by a factor of 2 (either way) about 2% of the time.

Therefore, it is desirable to conduct the Bayesian analysis next assuming that the scale parameter of the control distribution is unknown. The mathematics has been developed by Olsen (1975). We now assign a joint prior distribution to F and β_c, the control scale parameter. Moreover, the data now consist of two sets, seeded and control, so that Bayes equation should be written

$$p(F\,|\,\mathbf{x},\mathbf{y})=p(F,\beta_c)\frac{p(\mathbf{x},\mathbf{y}\,|\,F,\beta_c)}{p(\mathbf{x},\mathbf{y})}, \tag{4}$$

where **x** stands for the set of control data and **y** is the set of seeded data. For this analysis we choose an unfavorable prior on β_c, namely proportional to $1/\beta_c$. Since the expected value of the control distribution is inversely proportional to β_c, this choice places higher prior probabilities in the lower values of β_c, which would tend to reduce the estimated value of the seeding factor.

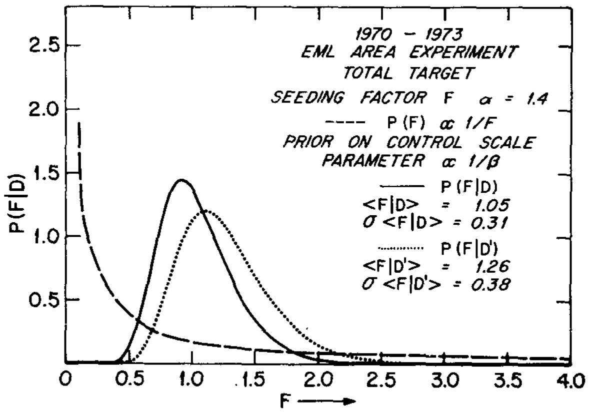

FIG. 7. As in Fig. 6 except for total target.

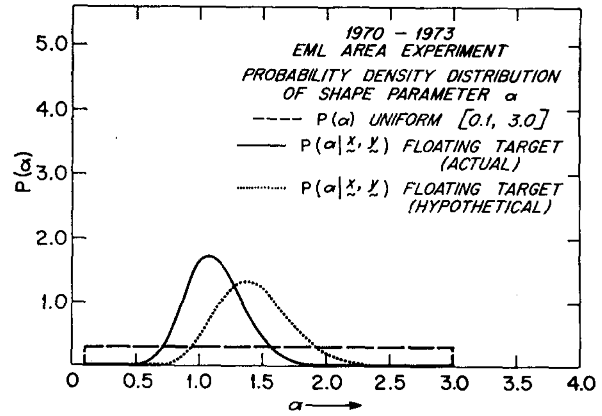

FIG. 8. Three-variable Bayesian analysis for floating target. Results for shape parameter α. Prior α dashed, uniform from 0.1 to 3.0; posterior α solid with actual data; dotted line is posterior α with hypothetical data set.

Figs. 6 and 7 show results of this analysis for floating and total target when prior F is chosen proportional to $1/F$. The differences between these results and those in Figs. 2 and 4 are imperceptible. Modal values of F are lowered a few percent; its standard deviation is increased by about 25%, and the 95% confidence limits are extended on both ends.

Although earlier work showed less sensitivity of the seeding factor to uncertainties in α than to those in the control scale parameter, there still remains a sizable variance in a shape parameter obtained by means of fitting a small data sample. Our most sophisticated Bayesian analysis to date involves allowing for uncertainty in α, the control mean, and F. The analysis has been developed in detail in a paper by Olsen *et al.* (1975). Symbolically, Bayes equation is now written

$$p(F\,|\,\mathbf{x},\mathbf{y})=p(F,\mu_c,\alpha)\frac{p(\mathbf{x},\mathbf{y}\,|\,F,\mu_c,\alpha)}{p(\mathbf{x},\mathbf{y})}. \tag{5}$$

For the calculation to be illustrated here, prior α is chosen uniform in the range 0.1 to 3. The prior for μ_c, the mean of the control distribution, is proportional to $1/\mu_c$, while prior F is proportional to $1/F$, as before.

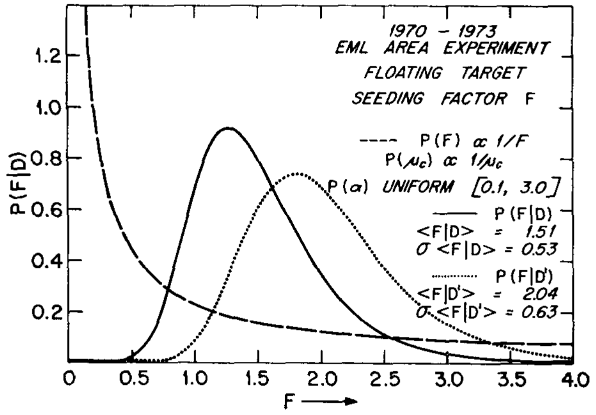

FIG. 9. Three-variable Bayesian analysis for floating target showing seeding factor F. Prior on α as in Fig. 8. Prior on μ_c (control mean) proportional to $1/\mu_c$. Dashed line is prior F, proportional to $1/F$; solid line posterior F with actual data; dotted line posterior F with hypothetical data.

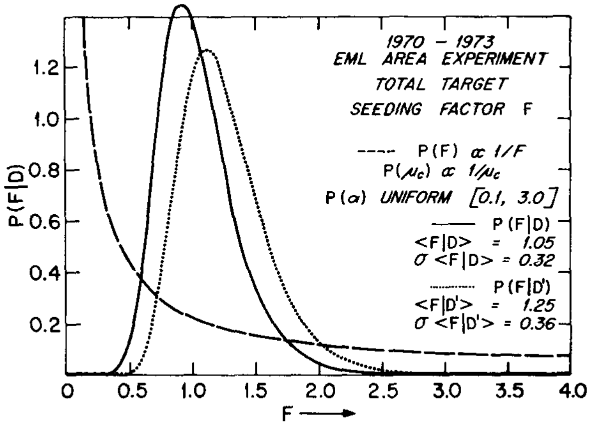

FIG. 11. As in Fig. 9 except for total target.

Results for the floating target are shown in Figs. 8 and 9, and for the total target in Figs. 10 and 11. With the actual data, good agreement for posterior α is obtained with the values shown in Table 6. The mean and modal values of F are little altered from the previous analyses. The standard deviations and 95% confidence intervals are virtually the same as the cases with α assumed known and control β unknown. A final interesting result is the integrated probability for posterior F, shown in Table 7.

The foregoing results are neither encouraging regarding the magnitude of the seeding factor, if any, nor are they encouraging regarding the potential rapidity of its resolution. It therefore seems imperative either to seek a more efficient experiment design or to improve analysis via covariates, predictors, data stratification or models.

Unfortunately, improved experiment design remains elusive. A study of the feasibility of randomized crossover (Woodley *et al.*, 1974, Part I) led to a negative prognosis owing to low correlations and, in particular, to the likelihood of "dynamic contamination" between targets.

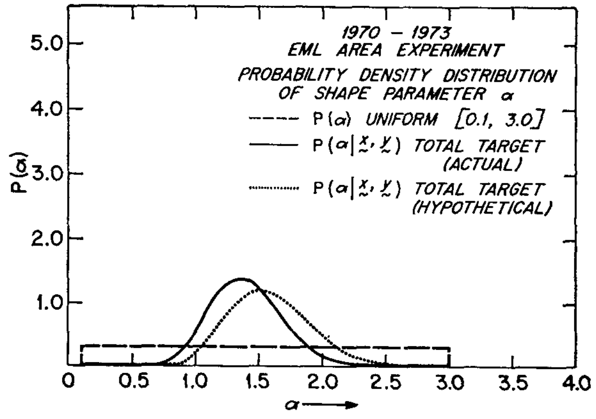

FIG. 10. As in Fig. 8 except for total target.

Hence the effort has been concentrated on seeking means of predicting and/or correcting for the natural rainfall variability. Efforts are underway to relate target rainfall to one or more measurables or model outputs which may, at least, separate very wet and very dry days, or in some manner mitigate the disastrous effects of the "heavy tail" of the rain distribution.

5. The search for covariates

With the EML single cloud experiments (Simpson *et al.*, 1971) the so-called "initial wetness," or rain from the cloud in the 10 min period prior to the seeding run, was a significant and successful covariate. For the area experiment, attempts are underway to find a similar empirical covariate and perhaps an additional one from a model, hopefully the Pielke three-dimensional simulation of the sea breeze over the south Florida peninsula (Pielke, 1974).

For the FACE 1970–72 data, an "initial wetness" variable combined with output from the EML one-dimensional cumulus model appeared promising (Woodley *et al.*, 1974, Part II). With the 1970–73 data, three types of "initial wetness" have been briefly examined: first, the rain in the target for 1 h preceding the first "seeding"; second, the rain in the target for the fixed time period 1200–1400 EDT; and third, the radar echo coverage upwind of the target at 0830 and 0930 EDT.

TABLE 7. Integrated probability for seeding factor F (from Bayesian analysis with priors on α, μ_c and F) for FACE 1970–73 data.

Floating target			Total target		
$p \leqslant 1$	$p \leqslant 1.2$	$p \leqslant 1.5$	$p \leqslant 1$	$p \leqslant 1.2$	$p \leqslant 1.5$
0.18	0.35	0.61	0.57	0.78	0.93

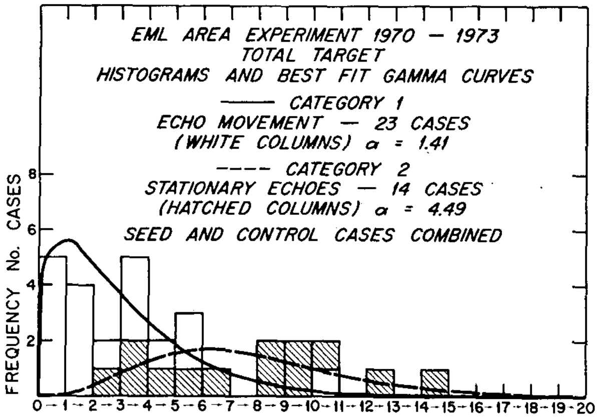

FIG. 12. Histograms and best fit gamma curves (seed and control combined) for Category 1 (marching echoes) and Category 2 (stationary echoes). GO days FACE 1970–1973. Category 1 is shown by unshaded columns and solid curve; category 2 by hatched columns and dashed curve. Rainfall units are in 10^7 m^3.

Regressions relating the first two to target unseeded rainfall gave sizable reduction in variance, but were not quite significant at the 5% level. The morning upwind echo coverage was uncorrelated with the target rainfall. This general approach, however, together with possible model output covariates will be pursued further.

Meanwhile, our experience with heated islands (Malkus and Stern, 1953; Stern and Malkus, 1953; Malkus, 1963), combined with a suggestion[6] that a "heavy-tailed" rain distribution might usefully be treated as two separate distributions, led to a breakthrough in data stratification. Over flat heated islands, days with strong wind flow generally do not permit the buildup of towering clouds and heavy showers.

On examining the radar echo motions with these concepts in mind, we found that the GO days were readily separable into "marching" and "stationary" days of radar echo behavior. Days could usually be classified using the radar scope tracings and notes thereon provided routinely by the National Weather Service radar observers. The same category (1 for "marching" and 2 for "stationary") was reached by independent analysis on most occasions prior to about 1400 local time, or before the time when the first seeding usually occurred. Examination of the radar film itself resolved the few ambiguous cases.

The category for each day is listed in the last column of Tables 2 and 3. Fig. 12 shows the histogram and the best fit gamma functions for the two rainfall populations (seed and control combined). With the Mann-Whitney-Wilcoxon test, the rain populations for the two types of days differ at a significance level better than 0.001. Table 9 shows the best fit gamma parameters for the two categories.

The most important demonstration is that category, as defined here, is a significant covariate for FACE rainfall. This result depends on the demonstration that the log-normal distribution is also a good fit to the FACE rainfall data,[7] so that the logarithms of the rain volumes are normally distributed. With this, Table 8 shows by one-way analysis of variance that category is a highly significant covariate.

In Table 8, SV stands for "source of variation," SS is "sum of squares," MS "mean squares," F is the F statistic, and α the significance level. Not only are the F values and significance levels remarkably good, but category accounts for 15% and 30% of the variation for the floating and total targets, respectively, which are very high values. The percentages are obtained from taking the ratio of the entry in the SS column in the Category row to the entry in the Total row. Although this result does not give direct or immediate information regarding the effects of seeding, it should enable a much sharper identification of these to be made from existing and future data.

Moreover, Tables 8 and 9 together suggest a possibility for further exploration, namely that the seeding effect might be different on the two types of days. Work in progress[8] indicates the likelihood that on "marching"

TABLE 8. One-way analysis of variance FACE 1970–73 data: category 1 versus category 2. [response is ln$R$ (in 10^3 m^3)]. See text for definition of symbols.

SV	DF	SS	MS	F
		A. Floating target		
Total	35	48.15		
Category	1	7.35	7.35	6.12
Error	34	40.80	1.13	
				$\alpha=0.02$
		B. Total target		
Total	35	39.76		
Category	1	11.94	11.94	14.59
Error	34	27.82	0.82	
				$\alpha\approx5.4\times10^{-4}$

TABLE 9. Stratification of cases into marching (1) and stationary (2) radar echoes.

	Comparison of rainfall distributions ($\times10^7$ m^3) α	β	$\bar{R}_S$	$\bar{R}_{NS}$	$\bar{R}_S/\bar{R}_{NS}$
Category 1 Marching: 10 seed, 13 control					
A. Floating target	1.05	0.606	2.07	1.49	1.39
B. Total target	1.41	0.440	3.72	2.76	1.35
Category 2 Stationary: 4 seed, 10 control					
A. Floating target	1.50	0.404	5.23	3.04	1.72
B. Total target	4.49	0.570	7.64	7.94	0.96

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[6] Dr. Ronald Biondini, personal communication.

[7] The log-normal distribution appears to fit the FACE rainfall data as well or better than the gamma distribution.

[8] By Dr. Ronald Biondini at the University of Virginia.

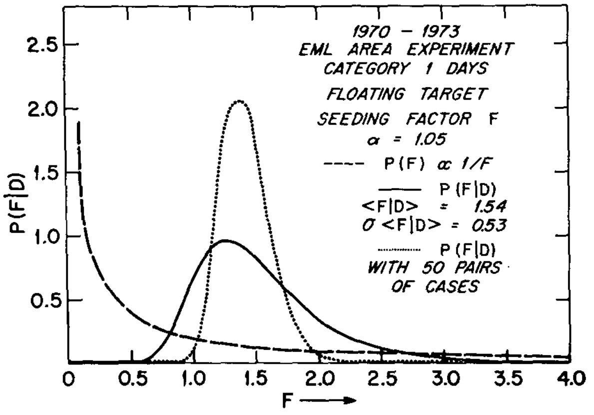

FIG. 13. Category 1 days, floating target. Bayesian analysis with prior F (dashed) proportional to $1/F$. Posterior F actual data solid curve. Dotted curve hypothetical posterior F if 50 pairs of cases gave same mean seeded and control rainfall values.

days it may not even be multiplicative in nature, but that seeding has so far acted to increase the variance in the rainfall data sample.

One of the major lessons learned in several important modification programs (Grant *et al.*, 1971; Dennis and Koscielski, 1969; Simpson *et al.*, 1971) is that the effects of seeding commonly differ with the initial conditions of the cloud-environment system and that a vital key to success is to learn to select out those conditions favorable to the modification hypothesis. Bayesian analyses for the stratified data are shown in Figs. 13–16.

The examples shown are for a prior probability on F only (proportional to $1/F$). Similar calculations were performed with priors on α and the control mean also. Results for F were virtually unchanged. However, in Category 2, the data sample was so small that the modal posterior values of α did not agree well with those of Table 9 obtained using maximum entropy (same result as obtained by maximum likelihood).

In Figs. 13 and 14 for Category 1 days, the dotted curves show what the posterior probability density distribution of F would look like if we had obtained the same average seed and control rainfall values as in Table 9, but with 50 pairs of experimental cases. In Figs. 15 and 16 for Category 2 days, we see that we might get good resolution with only 20 pairs of cases. This result can be deduced more generally from the properties of gamma functions. The larger the value of the shape parameter α, the fewer cases required to resolve a given seeding factor to a specified significance; this is because α is inversely related to the degree that the distribution is "heavy-tailed."

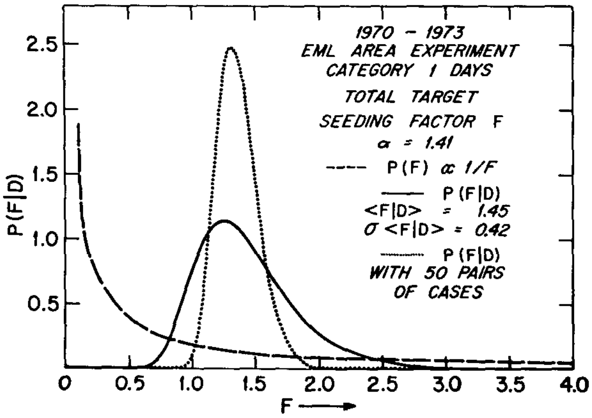

FIG. 14. As in Fig. 13 except for category 1 days, total target.

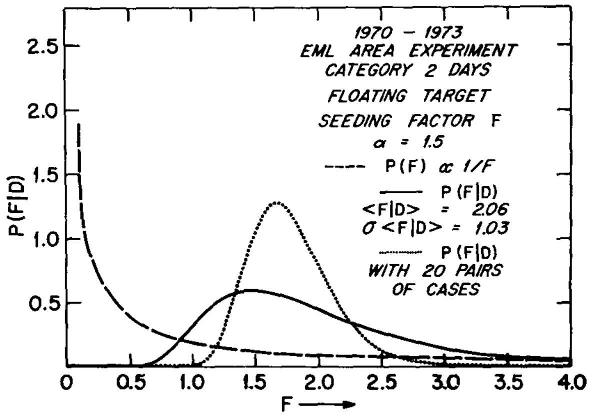

FIG. 15. Same as Fig. 13 except for category 2 days, floating target. Dotted line shows hypothetical posterior F if same mean values had been obtained with 20 pairs of cases.

6. Concluding remarks and future outlook

The core portion of the FACE experiment is clearly far from resolved as yet, in that it is not now possible to make a useful estimate of the seeding factor on the rainfall, either for the floating or the total target.

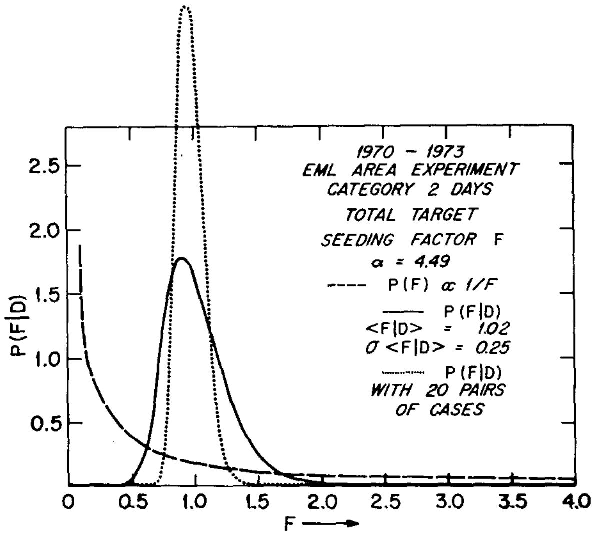

FIG. 16. As in Fig. 14 except for category 2 days, total target.

However, two effects of seeding and one covariate have been identified to a statistically significant level. The seeding effects are: 1) for non-merging clouds obtained in FACE, there is a factor of two more rainfall from seeded clouds; and 2) for merging clouds obtained in FACE, the seeded clouds merge more rapidly than the controls. Both effects support links in the chain of hypotheses related to the area experiment, namely that dynamic seeding promotes cloud growth and merger.

The covariate separates two different shower regimes on days selected as suitable for the experiment. These comprise Category 1 with marching echoes and Category 2, where echoes grow and die without significant advection. The data so far suggest that seeding effects may differ on these two types of days. Efforts to quantify the covariate in terms of echo speed and to include the direction of motion are progressing.

Further randomized experiments are planned in the Florida target in the summers of 1975 and 1976, which should double or triple the existing sample of 37 cases (14 seed, 23 control). The question of how many cases are necessary as an adequate sample to resolve various postulated seeding effects is being pursued,[9] with particular attention to the difficulties presented by heavy-tailed distributions, and will be reported in a sequel paper. Results so far provide hope that the planned two more seasons of experimentation will clarify the effects of seeding in this context, if successful operations and ingenious analyses are combined.

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REFERENCES

Bowman, K. O., and L. R. Shenton, 1970: Small sample properties of estimators for the gamma distribution. CTC-28, Computing Technology Center, Union Carbide Corp., Nuclear Division, Oak Ridge, Tenn., 160 pp.

Cotton, W. R., and A. Boulanger, 1974: On the variation of "dynamic seedability" as a function of time and location over south Florida. *Preprints Fourth Conf. Weather Modification*, Ft. Lauderdale, Fla., Amer. Meteor. Soc., 44–49.

Dennis, A. S., and A. Koscielski, 1969: Results of a randomized cloud seeding experiment in South Dakota. *J. Appl. Meteor.*, **8**, 556–565.

Grant, L. F., C. F. Chappell and P. W. Mielke, Jr., 1971: The Climax experiment for seeding cold orographic clouds. *Preprints Intern. Conf. Weather Modification*, Canberra, Australia, Amer. Meteor. Soc., 78–84.

Lhermitte, R., and R. I. Sax, 1974: Use of dual Doppler radar in the Florida area cumulus experiment. *Preprints Fourth Conf. Weather Modification*, Ft. Lauderdale, Fla., Amer. Meteor. Soc., 89–94.

Malkus, J. S., 1963: Tropical convection: Progress and outlook. *Proc. Symp. Tropical Meteorology*, Rotorua, New Zealand, New Zealand Meteorological Service, 247–277.

——, and M. E. Stern, 1953: The flow of a stable atmosphere over a heated island. Part I. *J. Meteor.*, **10**, 30–41.

Olsen, A. R., 1975: Bayesian and classical statistical methods applied to randomized weather modification experiments. *J. Appl. Meteor.*, **14**, 970–973.

——, J. Simpson and J. C. Eden, 1975: A Bayesian analysis of multiplicative treatment effect using two samples. *Technometrics*, **17**, 161–166.

——, and W. L. Woodley, 1975: On the effect of natural rainfall variability and measurement errors in the detection of seeding effect. *J. Appl. Meteor.*, **14**, 929–938.

Pielke, R., 1974: A three-dimensional numerical model of the sea breezes over south Florida. *Mon. Wea. Rev.*, **102**, 115–139.

Simpson, J., 1972: Use of the gamma distribution in single cloud rainfall analysis. *Mon. Wea. Rev.*, **100**, 309–312.

——, and V. Wiggert, 1969: Models of precipitating cumulus towers. *Mon. Wea. Rev.*, **97**, 471–489.

——, and ——, 1971: 1968 Florida cumulus seeding experiment: Numerical model results. *Mon. Wea. Rev.*, **99**, 87–118.

——, and J. Pezier, 1971: Outline of a Bayesian approach to the EML multiple cloud seeding experiments. NOAA Tech. Memo. ERL OD-8, 43 pp.

——, and W. L. Woodley, 1971: Seeding cumulus in Florida: New 1970 results. *Science*, **172**, 117–126.

——, ——, A. H. Miller and G. F. Cotton, 1971: Precipitation results of two randomized pyrotechnic cumulus seeding experiments. *J. Appl. Meteor.*, **10**, 526–544.

——, ——, A. R. Olsen and J. C. Eden, 1973a: Bayesian statistics applied to dynamic modification experiments on Florida cumulus clouds. *J. Atmos. Sci.*, **30**, 1178–1190.

——, J. C. Eden, A. R. Olsen and J. Pezier, 1973b: On the use of gamma functions and Bayesian analysis in evaluating Florida cumulus seeding results. NOAA Tech. Memo. ERL OD-15, 86 pp.

——, —— and ——, 1975: On the design and evaluation of cumulus modification experiments. *J. Appl. Meteor.*, **14**, 946–958.

Staff, Experimental Meteorology Laboratory, 1974: 1973 Florida Area Cumulus Experiment (FACE) operational and preliminary summary. NOAA Tech. Memo. ERL WMPO-12, 254 pp.

Stern, M. E., and J. S. Malkus, 1953: The flow of a stable atmosphere over a heated island, Part II. *J. Meteor.*, **10**, 105–120.

Tribus, M., 1969: *Rational Descriptions, Decisions and Designs*. Pergamon Press, 478 pp.

Woodley, W. L., 1970: Precipitation results from a pyrotechnic cumulus seeding experiment. *J. Appl. Meteor.*, **9**, 109–122.

——, J. Donaldson, J. Simpson, A. R. Olsen and J. C. Eden, 1974: On the design and evaluation of cumulus modification experiments. Part I—Precipitation correlations for two areas as background for cross-over experimentation in Florida. Part II—On the use of predictors and covariates. NOAA Tech. Memo. ERL WMPO-13, 65 pp.

——, A. R. Olsen, A. Herndon and V. Wiggert, 1975: Comparison of gage and radar methods of convective rain measurement. *J. Appl. Meteor.*, **14**, 909–928.

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[9] At the University of Virginia, by the first author, her colleague R. Biondini, and graduate student P. Rosenzweig.