A CRITICAL ASSESSMENT OF HYGROSCOPIC SEEDING OF CONVECTIVE CLOUDS FOR RAINFALL ENHANCEMENT

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The hygroscopic seeding hypothesis is not yet scientifically proven because it cannot explain the statistically significant increases in precipitation that were observed in recent experiments.

In Silverman (2001a) I conducted a critical assessment of glaciogenic seeding of convective clouds for rainfall enhancement. It was concluded that tests conducted so far have not yet provided either the statistical or physical evidence required to establish that the seeding concepts have been scientifically proven. Exploratory, post hoc analyses of some of the experiments have suggested positive effects of seeding under restricted meteorological conditions, at extended times after seeding and, in general, for reasons not contemplated in the guiding conceptual seeding models. However, these exploratory results have never been confirmed through subsequent experimentation.

On the other hand, in Silverman (2001b) I was cautiously optimistic about recent reports on the statistical evaluation of hygroscopic seeding experiments. I found it noteworthy that statistically positive results were reported in three hygroscopic seeding experiments in three different parts of the world (South Africa, Mexico, and Thailand), and that it was necessary to invoke the occurrence of seeding-induced dynamic effects to explain the results in all cases [Board of Atmospheric Sciences and Climate (BASC) 2000; World Meteorological Organization (WMO) 2000]. I found particularly remarkable the preliminary indication that the Mexico hygroscopic flare seeding experiment appeared to have replicated the pattern of results obtained in the South Africa hygroscopic flare seeding experiment (Bruintjes et al. 1999, 2001; Fowler et al. 2001). At the same time, I recognized the tentative nature and limitations of the reported results. Although the statistical results of the Thailand experiment are unequivocally significant, those of the South African and Mexico experiments had yet to take into account the potential effects of multiplicity of analyses. I concluded that a critical assessment of the statistical results of these experiments is needed in order to draw sound conclusions about their statistical significance. The importance of such a critical assessment is underscored by the fact that

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another hygroscopic seeding experiment (Murty 2000) in yet another part of the world, for example, India, reported statistically positive results.

The purpose of this paper is to critically assess the scientific status of the hygroscopic seeding concept. As before, this assessment uses, as a measure of proof of concept, the criteria for success of any cloud seeding activity that were recommended in the scientific background for the AMS Policy Statement on Planned and Inadvertent Weather Modification (AMS 1998). As before, the assessment focuses on those experiments for which the experimenters reported statistically positive results. In some ways this assessment is an update of the reviews of hygroscopic seeding of convective clouds by the WMO (1981, 1984), Cotton (1982), Czys and Bruintjes (1994), and Bruintjes (1999), all of which concluded in one way or another that past hygroscopic seeding efforts have not yet provided the scientific evidence that hygroscopic seeding increases precipitation, although some suggest positive effects and some suggest that the observed effects were generally consistent with the hygroscopic seeding hypothesis under investigation. Although there are many aspects of hygroscopic seeding experiments that are open to critical assessment (e.g., the design and execution of the experiments with respect to their seeding conceptual models), the primary focus of this assessment is on the results of the experiments.

As in Silverman (2001a), the statistical assessment criteria that are used in this critical review are based on the guidance provided by statisticians to the weather modification community (see, e.g., Tukey et al. 1978; Braham 1979, including the associated comments; WMO 1980; Gabriel 1981, 2000, 2002). I emphasize the results of randomized statistical experiments conducted and evaluated in accordance with their a priori design. When the a priori design specifies or implies more than one hypothesis for testing/analysis, the statistical level of significance (usually 0.05) will be adjusted to account for multiplicity of hypotheses/analyses. This critical review will use the Bonferroni method (see, e.g., Gabriel 2000; Silverman and Sukarnjanaset 2000), whereby the statistical level of significance is shared equally among the number of hypotheses/analyses indicated.

STATISTICAL EVIDENCE. This assessment will focus on four major, randomized hygroscopic seeding experiments, each in a different part of the world. Experiments on cold convective clouds using hygroscopic flares were carried out in South Africa and Mexico. Experiments on warm convective clouds using hygroscopic particles were carried out in Thailand and India. Each experiment reported statistically positive results. Potential uncertainties in the evaluation of these experiments are discussed in the appendix.

The South Africa hygroscopic seeding experiment. REPORTED FINDINGS. The South Africa hygroscopic seeding experiment (Mather et al. 1997a,b) was launched during the 1991/92 field season and continued for 5 yr. It was a randomized experiment, based on a floating target design, in which the experimental units were convective storms located within about a 100-km radius of C-band radars located at Bethlehem in the Free State and Carolina in the Eastern Transvaal. All storms selected for random treatment (seed or no-seed) were producing a radar echo before seeding began and most of them were already raining. The convective storms were seeded at cloud base with hygroscopic flares that produce small salt particles of about 0.5-μm mean diameter. During the experiment 127 storms were treated, 62 seeded and 65 nonseeded.

Assuming that radar-estimated rain mass production is proportional to storm size, Mather et al. (1997b) reported that the smaller cloud systems appeared to respond to treatment first, the medium size cloud systems a little later, and the largest cloud systems last. Based on the results, Mather et al. (1997b) claimed that they had shown that rainfall could be increased from individual storms by hygroscopic flare seeding. In an independent statistical assessment of the experiment, Bigg (1997) confirmed Mather et al.'s (1997b) finding. In an independent statistical reevaluation of the experiment, Silverman (2000) also found nothing that contradicted the claim by Mather et al. (1997b).

CRITICAL ASSESSMENT. Mather et al. (1997a) stated that the most useful analyses would be to examine the differences between seeded and unseeded storms in 10-min time windows before and after decision time in order to determine whether there were any inadvertent selection biases and to check the validity of the differences for physical consistency as they evolve from one time window to the next. Since most of the storms were seeded in the first 20 min after decision time, they stated that it was unreasonable to attribute to seeding any differences in rain flux at cloud base in the first 10 min after decision time.

Based on the design document and its addendum (Mather et al. 1997a), I have concluded that the a priori evaluation of the South Africa hygroscopic seeding experiment should be based on a means analysis of the five 10-min time windows between 10 and 60 min after decision time. The multiplicity of hypotheses will have to be taken into account in the interpretation of the results. It also means that the previous evaluation that was based on quartile analyses must now be regarded as an exploratory analysis, the results of which do not qualify as valid probabilistic assessments (Gabriel 2002). As a result, I reevaluated the South Africa hygroscopic seeding experiment in accordance with the a priori design using rerandomization procedures to obtain a valid statistical assessment of the experiment.

It can be seen from Table 1 that the seeding effects and *p* values[1] in the 10-min time intervals from 20 to 60 min after decision time are quite impressive. The proportional effect of seeding and its statistical support increase steadily from 20 to 60 min after decision time, with the seeding effect (SR-1) in the 40–50-min time interval being statistically significant against the stringent Bonferroni level of significance. An analysis of the cumulative rain mass from 0 to 60 min indicated a proportional effect of seeding (SR-1) = 0.59, $p = 0.026$, and (RR-1) = 0.41, $p = 0.038$. The RR-1 results are exploratory and the *p* values are shown only to indicate the strength of the effect. They were done to make sure that the a priori SR-1 results were not due to the effects of the "potentially compromising covariant," the fact that the rain mass for the seeded clouds was higher than that of the unseeded clouds in the 10-min time interval before decision time.

To gain insight as to which type of clouds might be responding most favorably to seeding, the data were partitioned according to experimental area (Bethlehem and Carolina) and size of storm at the time of selection, and analyzed accordingly. The results of the means analysis based on these partitions are given in Table 2. All the results are exploratory, and the *p* values are shown only to indicate the strength of the effect. Bethlehem cloud systems appear to have responded much more favorably to seeding than Carolina cloud systems. Hygroscopic flare seeding may not have been as effective on Carolina cloud systems because they are closer to the Indian Ocean; however, this must be considered a matter of speculation in the absence of confirming data. It can also be seen that hygroscopic flare seeding had no apparent effect on cloud systems whose volumes at the time of selection exceeded 750 km^3. Seeding is apparently too little and too late when applied to storms that are already so large at the time of selection. Most striking about these results is that the evaluation of the overall experiment seems to be driven by the very strong effect of seeding on Bethlehem storms whose volumes at the time of selection were ≤ 750 km^3.

This evaluation in accordance with its original design reaffirms the claim by Mather et al. (1997b) that there is statistical evidence that hygroscopic flare seeding increased rain mass in the experiment.

[1] The probability that a variate would assume a value greater than or equal to the observed value strictly by chance.

Table 1. Results of the 10-min time interval evaluation based on means analysis in accordance with the a priori design of the South Africa hygroscopic seeding experiment. The proportional effects of seeding (SR-1) are shown along with their *p* values. The proportional effects of seeding (RR-1) are also shown along with their *p* values. The RR-1 results represent the SR-1 time interval evaluation results adjusted for the effects of the "potentially compromising covariant," the fact that the rain mass for the seeded clouds was higher than that of the unseeded clouds in the 10-min time interval before decision time [SR-1 = .36, *p* = 0.174)]. Values of SR-1 with *p* values ≤ 0.01, the Bonferroni level of significance (0.05/5) for each hypothesis, are shown in bold italics.

Interval (min)	SR-1	*p* value	RR-1	*p* value
10–20	0.21	0.192	0.06	0.252
20–30	0.38	0.096	0.23	0.096
30–40	0.62	0.038	0.50	0.032
40–50	1.16	***0.006***	1.04	0.006
50–60	1.33	0.014	1.22	0.020

Table 2. Evaluation of the 0–60-min rain mass results partitioned by experimental area and storm volume at decision time, adjusted for the effects of the potentially compromising covariant. Values are for RR-1, with *p* value in parentheses below.

Storm volume	Experimental area		
	Both	Carolina	Bethlehem
Both	0.41 (0.044)	0.27 (0.173)	0.53 (0.069)
Small (750 km^3)	1.25 (0.001)	0.30 (0.162)	3.20 (0.000)
Large (>750 km^3)	–0.07 (0.364)	0.14 (0.332)	–0.25 (0.243)

The Mexico hygroscopic seeding experiment. REPORTED FINDINGS. The Mexico hygroscopic seeding experiment (Bruintjes et al. 1999, 2001), also known as the Program for the Augmentation of Rainfall in Coahuila (PARC), was conducted in the State of Cohuila in the north of Mexico during the summers of 1997 and 1998. It was a randomized experiment on convective storms, based on a floating target design, aimed at replicating the South African hygroscopic seeding experiment (Mather et al. 1997b). As such, the same experimental procedures were used in PARC as were used in the South African hygroscopic seeding experiment, including the same experimental unit selection criteria, seeding procedures, flare design, and randomized scheme. In addition, pilots with experience in South Africa flew the aircraft in PARC. During the experiment 99 storms were treated, 47 seeded and 52 nonseeded.

Like the South African experiment, the evaluation of PARC was based on the amount of radar-estimated rain mass produced by the convective cloud complexes. Bruintjes et al. (2001) showed that the pattern of results for PARC and for South Africa were remarkably similar. Rerandomization tests by Fowler et al. (2001) indicated that several of the differences between average seeded and average nonseeded rain mass were statistically significant (one-tailed p value ≤ 0.05), especially for the second and third quartiles between 20 and 50 min after selection. Fowler et al. (2001), testing the log of rain mass data, found that both the mean and median of the seeded group were significantly greater (one-tailed p value ≤ 0.05) than those of the unseeded group. Further tests of the differences between the two groups indicated that they were not significant for both the small and largest storms, but significant for the median storms. Fowler et al. (2001) were quick to point out that multiple comparisons were made and, therefore, some are likely to yield significant results purely by chance.

CRITICAL ASSESSMENT. The multitude of response variables and hypotheses specified for testing included radar-estimated precipitation flux, total storm mass, storm mass above 6 km MSL, storm area, and height of maximum reflectivity minus Z-weighted vertical centroid (NCAR–RAP 1997). The statistical hypothesis was that the seeded cases would demonstrate an increase in these response quantities over the unseeded cases 20 to 50 min from decision time. Three other cumulative radar response variables were specified: 1) total precipitation from decision time to the end of the experimental unit, 2) area–time-integral from decision time to the end of the experimental unit, and 3) duration of the experimental unit from decision time to a maximum of 60 min after decision time. Again, seeded cases were hypothesized to demonstrate an increase in the response quantity over the unseeded cases. After applying the Bonferroni method to partition the significance level of 0.05 among all the specified tests, it is unlikely that any test could satisfy the resulting level of significance. On the other hand, with such a large number of tests, some are likely to yield significant results purely by chance.

In view of the above considerations, no attempt was made to reevaluate the Mexico hygroscopic seeding experiment in accordance with its design. Instead, I repeated the reevaluation for the South Africa experiment (Table 1) for the Mexico experiment since it was designed, in essence, to replicate it. Since every effort was made to replicate all aspects of the execution of the South African experiment, it was logical to see how well the evaluation would be replicated.

It can be seen from Table 3 that the statistical results of the Mexico experiment are quite positive. The seeding effect seems to peak earlier statistically in the Mexico experiment than in the South Africa experiment. This seems to this author to be more consistent with the pattern one would expect from the seeding hypothesis. An analysis of the cumulative rain mass from 0 to 60 min indicated a proportional effect of seeding (SR-1) = 0.58, $p = 0.058$, and (RR-1) = 0.43, $p = 0.010$, comparable to that of the South Africa experiment.

These exploratory results notwithstanding, one must conclude that the evaluation results of the Mexico hygroscopic seeding experiment did not replicate the results of the South African experiment because the great multiplicity of hypotheses specified in the design make it virtually impossible for any of the hypotheses to attain statistical significance against the stringent Bonferroni level of significance.

The Thailand warm cloud seeding experiment. REPORTED FINDINGS. A randomized, warm rain enhancement experiment was carried out during 1995–98 in the Bhumibol catchment area in northwestern Thailand (Woodley et al. 1999). The seeding targets were semi-isolated, warm convective clouds contained within a well-defined experimental unit. Randomized seeding was done by dispensing calcium chloride particles at an average rate of 21 kg km^{-1} per seeding pass into the updrafts of growing warm convective clouds (about 1–2 km above cloud base) that had not yet developed or, at most, had just started to develop a precipitation radar echo. Volume scan data from a 10-cm Doppler radar at 5-min intervals were used to

TABLE 3. Results of the 10-min time interval evaluation based on means analysis for the Mexico hygroscopic seeding experiment as was done for the South Africa hygroscopic seeding experiment. The proportional effects of seeding (SR-1) are shown along with their *p* values. The proportional effects of seeding (RR-1) are also shown along with their *p* values. The RR-1 results represent the SR-1 time interval evaluation results adjusted for the effects of the potentially compromising covariant, the fact that the rain mass for the seeded clouds was higher than that of the unseeded clouds in the 10-min time interval before decision time (SR-1=0.13, *p* =0.342).

Interval (min)	SR-1	*p* value	RR-1	*p* value
10–20	0.42	0.072	0.29	0.004
20–30	0.56	0.094	0.42	0.006
30–40	0.91	0.038	0.73	0.014
40–50	0.72	0.088	0.56	0.032
50–60	0.86	0.098	0.68	0.046

track each experimental unit. During the four years of the experiment, a total of 67 experimental units (34 seeded and 33 nonseeded units) were qualified in accordance with the a priori design.

The statistical evaluation of the experiment was based on a rerandomization analysis of the single ratio of seeded to unseeded experimental radar-estimated rain volume at cloud base. The warm cloud seeding experiment was designed to test the following two null hypotheses: H01 (calcium chloride seeding does not alter the total rainfall volume per experimental unit 30 min after terminating treatment of the units) and H02 (calcium chloride seeding does not alter the total rainfall volume per experimental unit over the lifetime of the units). It was found that the proportional effect of seeding under H01 was 10%, with a *p* value of 0.44. The proportional effect of seeding under H02 was 109%, with a *p* value of 0.02. Since the experiment included two a priori null hypotheses, rigorous statistical practice required that the 5% level of significance be partitioned equally among the two null hypotheses according to the Bonferroni method, so a level of significance of $p = 0.025$ was assigned to each. It was, therefore, concluded that H02 could be rejected whereas HO1 failed to reject the null hypothesis.

CRITICAL ASSESSMENT. With a *p* value of 0.44 the first hypothesis could not be rejected at the Bonferroni level of significance of 0.025. On the other hand, the second hypothesis resulted in a 109% increase in radar-estimated rain volume, with a *p* value of 0.02, so it could be rejected at the Bonferroni level of significance of 0.025. The Thailand experiment provided statistically significant evidence that hygroscopic particle seeding can increase the rainfall from warm convective clouds.

The India warm cloud seeding experiment. REPORTED FINDINGS. A warm cloud modification experiment was carried out during the 11 summer monsoon seasons (1973–74, 1976, 1979–86) in the Maharashtra State of India (Murty et al. 2000). It was a randomized crossover experiment with two 1600 km^2 target areas (north and south) separated by a buffer area, the size of each area being 1600 km^2. On a day declared to be an experimental day, the clouds (stratocumulus and cumulus) in the randomly selected target area were seeded with 1000 kg of finely pulverized sodium chloride particles about 10 μm in diameter dispensed from an aircraft at a height of about 200–300 m above cloud base at a rate of 3.33 kg km^{-1} (in concentrations of about 1–10 L^{-1} of cloudy air depending on existing dispersion conditions). During the 11 yr of the experiment there were 160 experimental days.

The evaluation of the experiment was based on the 24-h rainfall measured by 90 rain gauges. The effect of seeding was obtained from the root double ratio (RDR). It was found that the proportional effect of seeding (RDR-1) was 24%, with a *p* value of 0.04.

CRITICAL ASSESSMENT. As far as this author can determine from the published literature (Murty et al. 2000; Selvam et al. 1979), the experiment was carried out and evaluated in accordance with its original design. This author tried to obtain copies of the original data from P. C. S. Devara, the corresponding author of Murty et al. (2000), in order to do an independent evaluation of the experiment. Unfortunately, the data could not be provided because the personnel who were involved in the experiment and its analysis had retired (P. C. S. Devara 2002, personal communication). There is however, no reason to doubt the evaluation of the randomized crossover area experiment by Murty et al. (2000).

There is, however, cause for concern. An examination of the data presented by Murty et al. (2000) indicates a great disparity in results when the north and south target areas are evaluated separately. The single ratio for the north target is 1.649 while the single ratio for the south target is 0.923, results that are reminiscent of the results of the Israel-2 experiment (Gabriel and Rosenfeld 1990). Why the two areas responded so differently to seeding requires a physical explanation.

PHYSICAL EVIDENCE. The physical hypothesis for all of the above-mentioned hygroscopic seeding experiments was based on the static-mode seeding concept, or seeding for microphysical effects. It was postulated that the hygroscopic particles would act to increase the efficiency of the rain formation process by accelerating the condensation–coalescence–collision process in the cloud. In the case of the South Africa and Mexico experiments this was attempted by introducing cloud condensation nuclei to affect the condensation process by broadening the initial cloud drop size spectrum to promote the competition effect, whereas the Thailand and India experiments attempted to do this by introducing ultragiant condensation nuclei to jump start the collision–coalescence process. Both would, in turn, promote the earlier development of precipitation particles and the harvesting of more of the available water in the cloud to produce more rain than would occur naturally. Each of the experiments did, in fact, produce some evidence that indicated that hygroscopic seeding tended to promote the broadening of the cloud droplet spectra and earlier development of precipitation embryos.

The South Africa hygroscopic seeding experiment. REPORTED FINDINGS. Prior to the start of the South Africa seeding experiment, seeding trials were conducted to test the seeding hypothesis that the release of small hygroscopic seeding particles into the updraft at cloud base would accelerate or enhance the formation of precipitation via coalescence in seeded clouds (Mather et al. 1997b). A Learjet was used to sample the updraft of treated (seeded and unseeded) clouds at about the −10°C level. Many instances were recorded of large drops appearing at the Learjet sampling level shortly after seeding began at cloud base.

After finding that the initial results of the South Africa seeding experiment appeared to be positive, a special measurement program was conducted to examine the cloud drop spectrum in the treated (seeded and unseeded) plume about 200 m above cloud base (Mather et al. 1997b). The measurements from one important case showed that the material from the hygroscopic flares had dramatically altered the drop spectrum, presumably by lowering the peak supersaturation reached in the lower layers of the cloud. This, in turn, reduced the number of natural cloud condensation nuclei that were activated, resulting in condensation on fewer but larger droplets. The results from these microphyscial measurements were supported by numerical condensation–coalescence calculations by Cooper et al. (1997) that suggested that the formation of rain through the warm-rain process could be accelerated significantly by the addition of hygroscopic particles produced by the South Africa flares. It is, however, emphasized that the microphysical measurements were not a concomitant part of the randomized experiment. They were made in a separate experiment in which the storm size and seeding concentration were not representative of the storms and seeding concentrations used in the randomized experiment. These physical measurements cannot, therefore, be used as physical evidence to substantiate the physical plausibility of the statistical results of the randomized experiment.

CRITICAL ASSESSMENT. Mather et al. (1997b) found that the seeded storms lasted longer than the unseeded storms. Bigg (1997) postulated that the hygroscopic seeding produces rainfall earlier and at a lower level in the seeded clouds, which causes a stronger and more localized downdraft to form much closer to the updraft, and the resulting gust front interacts with the low-level inflow to trigger new and more vigorous cloud growth on the flanks of the treated storms. Mather et al. (1997b) concluded, however, that invoking a dynamic effect at this stage was hypothetical because there were no physical measurements that support such an effect.

The Mexico hygroscopic seeding experiment. REPORTED FINDINGS. Prior to the start of the Mexico hygroscopic seeding experiment, an instrumented cloud physics aircraft was used during the summers of 1996 and 1997 to obtain measurements of the microphysical characteristics of summertime convective clouds in the State of Coahuila, Mexico (Breed et al. 1999). The measurements indicated that the clouds in Coahuila were fairly similar to the South African clouds. Based on these findings and the modeling studies of Cooper et al. (1997) it was concluded that there was a reasonable physical basis for attempting to replicate the South Africa experiment with a randomized experiment in Coahuila.

CRITICAL ASSESSMENT. Bruintjes et al. (1999) also found that seeded clouds tended to live longer than unseeded clouds in the Mexico experiment. They reported that the statistical results could be physically explained by the microphysical seeding hypothesis until about 30 min after decision time but could not explain the apparent seeding effect beyond 30 min.

They speculated that this may indicate a dynamic response beyond the initial production of precipitation but could offer no physical measurements to support their supposition.

The Thailand warm cloud seeding experiment. REPORTED FINDINGS. The design of the Thailand hygroscopic seeding experiment was guided by the results of the numerical model experiments by Rasmussen et al. (1989), Silverman et al. (1994), and Silverman and Sukarnjanaset (1996) that indicated that large hygroscopic particle seeding leads to improved precipitation efficiency of the warm convective clouds. Of the four hygroscopic chemicals investigated (calcium chloride, ammonium nitrate, sodium chloride, and urea), seeding with dry calcium chloride particles produced the largest effects. It was found that seeding with readily purchased, inexpensive, relatively large-size, polydisperse calcium chloride particles (see Table 1 of Silverman and Sufkarnjanaset 2000) produced smaller seed/no-seed ratios than seeding with more optimum sized monodisperse particles; nevertheless, experimentally observable seed/no-seed ratios were still predicted. It was found that seeding near cloud base with calcium chloride particles produced larger seed/no-seed ratios than near-cloud-top seeding and that the seed/no-seed ratios increase with increasing concentration or dosage. It was also found that seeding with calcium chloride particles is most effective when conducted early in the life of a growing cloud, before the development of a natural radar echo. These model results agreed in principle with the model experiments of Tzivion et al. (1994), who used a 3D axisymmetric model to simulate hygroscopic particle seeding in a convective cloud.

CRITICAL ASSESSMENT. Silverman and Sukarnjanaset (1996) found that the main seeding effects were in the untreated clouds in the experimental units that they concluded were subsequently spawned by the treated clouds. Because the apparent seeding effect showed up in untreated clouds hours after it was expected according to the seeding conceptual model, the possibility that the rain actually came from dynamically unrelated clouds that originated outside the target area was investigated and ruled out. They concluded that the microphysical seeding hypothesis, as originally stated, needed to be revised to include a dynamic-effect component in the seeding hypothesis.

Silverman and Sukarnjanaset (1996) postulated that seeding warm convective clouds with commercially available, relatively large polydisperse calcium chloride particles would accelerate the coalescence process by initiating the collision–coalescence process earlier in the life of the cloud. By reducing the time required for the precipitation process to evolve with respect to the time available, rain efficiency will increase such that the treated clouds will precipitate earlier and with greater intensity than they would naturally, but they may not necessarily produce more rain than they eventually would naturally. The change in the timing (and location) and/or increased intensity of the rain or alteration in the size spectrum of raindrops may produce an enhanced downdraft, the gust front from which will trigger the successive development of more vigorous second-, third-, and fourth-generation cells than those from unseeded clouds, and they will produce more rain than their unseeded counterparts. Since there is no physical evidence to support this new seeding hypothesis, it must be considered a matter of speculation for now.

The India warm cloud seeding experiment. REPORTED FINDINGS. In the India experiment (Murty 2000), it was found that the unseeded clouds had giant cloud condensation nuclei (GCCN) concentrations of 2.8 L^{-1} (standard deviation of 1.2 L^{-1}), which was approximately the same as the background concentration of about 2 L^{-1}, whereas the GCCN concentration in the seeded clouds was 5.0 L^{-1} (standard deviation of 2.3 L^{-1}). Therefore, it was concluded that the seeded clouds had an advantage in the initial development of precipitation-size drops in accordance with the seeding hypothesis.

The concentration of cloud drops in all size groups increased more rapidly in the seeded than unseeded clouds in the 15–20 min following seeding, especially in the large drop sizes (diameters > 40 μm), and the average median volume diameter increased more rapidly as well. The liquid water content and updraft velocities were higher in the seeded clouds. Murty (2000) suggested that this was physical evidence in support of the possibility that the hygroscopic particle seeding was accelerating the condensation–coalescence process in accordance with the seeding hypothesis.

It is important to emphasize that the physical evidence provided by Murty et al. (2000) in support of the seeding hypothesis was derived from physical observations in pairs of seeded and unseeded clouds that were not part of the randomized crossover area experiment. In addition, the seeding rate used in the physical evaluation studies appears to be almost an order of magnitude higher than that used in the randomized crossover area experiment. Given the difference in seeding rates and the lack of concomitant physical measurements in the randomized crossover area experiment, the physical evidence provided by Murty et al. (2000) cannot be used to substantiate the physical plausibility of the statistical results of the randomized crossover experiment.

Critical assessment. The warm cloud seeding experiment in Maharashtra discussed here was the second of two randomized seeding experiments that were carried out in India. The first experiment was carried out during the summer monsoon seasons of 1957–66 in the Delhi, Agra, and Jaipur regions of northwest India. Statistical evaluation of that experiment indicated a 21% increase in seasonal precipitation, with a p value of 0.005 (Murty et al. 2000; Biswas et al. 1967). Few scientists accepted this result as being scientifically credible because they doubted that the microphysical seeding hypothesis could explain increases in precipitation of that magnitude. Mason (1971) pointed out that "the number of salt particles injected into the clouds cannot have been sufficient to produce a detectable amount of rain even if each grew into a large raindrop." Cotton (1982), on the other hand, stated, "While the results of the Indian experiments must still be viewed as ambiguous, they cannot be thrown out as invalid." For similar reasons, it is possible that the statistical results of the warm cloud seeding experiment in Maharashtra cannot be explained by the microphysical seeding hypothesis. An alternative physical hypothesis may be needed to explain the statistically significant results from the two Indian experiments. It is tantalizing to think that dynamic effects played a part in producing those results, as they were postulated to do in the South Africa, Mexico, and Thailand experiments, but there is no physical evidence to support that hypothesis.

SUMMARY AND CONCLUSIONS. A critical assessment of the statistical results of these four randomized experiments, evaluated in accordance with their original designs, confirms that statistically significant increases in precipitation were produced in the South Africa, Thailand, and India experiments. Statistically significant results were obtained in these experiments even after taking multiplicity of hypotheses/analyses into account. Although the exploratory statistical results of the Mexico experiment were quite positive, it was deemed unlikely that the a priori hypotheses could be found to be statistically significant because of the great multiplicity of hypotheses specified in the design. As a result, it is concluded that the Mexico experiment failed to replicate the South Africa experiment as intended. It should be noted that the results of the Mexico experiment would have been statistically significant if its design specified the same statistical hypotheses as those in the South Africa experiment. Since the Mexico experiment strove to replicate all other aspects of the South Africa experiment, it is puzzling that it did not specify a replication of the statistical hypotheses as well. In my opinion, the statistical results of the four experiments are quite remarkable, especially when one considers that the experiments are quite diverse in geographical location, in meteorological setting, in design, and in experimental and evaluation procedures.

A critical assessment of the physical evidence that supports the statistical results of these four experiments is, on the other hand, rather disappointing. All four experiments provided evidence through physical observations and/or numerical cloud model calculations that hygroscopic seeding could act to accelerate the condensation–coalescence process and promote the earlier development of precipitation-size drops in accordance with the physical hypothesis of seeding for microphysical effects. None of the physical observations were taken as a concomitant part of the randomized experiments. None of the experiments were able to provide physical evidence linking the seeding intervention to the observed increases in precipitation from the clouds as postulated by the microphysical seeding hypothesis. On the contrary, dynamic effects had to be invoked to explain the increase in precipitation that was observed in the South Africa, Mexico, and Thailand experiments, but there was no physical evidence to support that speculation. An alternative physical hypothesis was not offered to explain the statistically significant seeding effect in the India experiment.

Based on a critical examination of the results of the four major, randomized hygroscopic seeding experiments that were reported during the past decade, it has been concluded that they have not yet provided either the statistical or physical evidence required to establish that hygroscopic seeding of convective clouds to increase precipitation is scientifically proven. The impressive statistical results must be viewed with caution because, according to the proof-of-concept criteria, credibility of the results depends on the physical plausibility of the seeding conceptual model that forms the basis for anticipating seeding-induced increases in rainfall. The credibility of the static-mode hygroscopic seeding conceptual model has been seriously undermined because it cannot explain the magnitude and timing of the statistically significant increases in precipitation that were observed. Theories suggesting that the microphysical effects of seeding-enhanced downdraft circulations to produce longer-lived clouds have been advanced; however, in the absence of any supporting physical or model evidence, they must be considered to be in the realm of speculation.

The recommendations of Silverman (2001a) for the further development of the hygroscopic seeding technology are repeated here for emphasis. The WMO convened a workshop on hygroscopic seeding (WMO 2000) to review the hygroscopic seeding experiments carried out in South Africa, Thailand, and Mexico, and to develop a program plan for moving ahead with this technology. In particular, it focused on a program to obtain an understanding of the chain of physical events that was responsible for the statistical results and, based on that understanding, to design a physical–statistical experiment to demonstrate that increases in rainfall could be achieved on an area-wide basis as well as from individual convective clouds and storms. In general, a better understanding of how the timing, location, and intensity of downdrafts affects the autopropagation of a convective cloud system is needed. The development and evaluation of a viable physical hypothesis should be strongly supported by the use of suitable numerical cloud models covering all scales of interaction that are involved. High priority should be given to the implementation of this program plan.

These results do not alter my basic position; I continue to advocate cloud seeding in situations where it is scientifically and operationally appropriate, and strongly recommend that an independent evaluation accompany each research or operational project in order that the science of weather modification benefit from the experience. The purpose here (as in Silverman 2001a) is to identify gaps in the statistical and physical evidence required to establish proof of concept, gaps that future projects should address. On a higher level, the purpose of these papers was to instigate discussion and debate that would lead to a consensus in the meteorological community, not just the weather modification community, as to the criteria for establishing proof of concept. In my experience, this means different things to different people. By reaching a common understanding of what constitutes proof of concept, I hoped, perhaps naively, that everyone would be compelled to agree that it had been achieved when the specified criteria have been satisfied, including the doubters and skeptics among us.

The AMS Policy Statement on Weather Modification (AMS 1998) called for both statistical and physical evidence as proof of the success of any cloud seeding experiment. In my opinion, the statisticians have provided unambiguous, objective statistical criteria for evaluating a weather modification experiment, the application of which has yielded positive results for several experiments. The criteria for evaluating the physical evidence are, on the other hand, very ambiguous and highly subjective. The establishment of unambiguous, objective physical evaluation criteria is needed to confirm that the effects of seeding suggested by results of the statistical experiment were likely caused by the seeding intervention, that is, that the physical evidence is consistent with the statistical evidence. I recommend that the physical evaluation criteria be based on physical observations taken as an integral part of the randomized experiment in order to verify pivotal links in the chain of physical events associated with the seeding conceptual model.

APPENDIX: POTENTIAL EVALUATION UNCERTAINTIES. The evaluation of the South Africa, Mexico, and Thailand experiments was based on estimates of rainfall from radar, whereas rain gauge estimates of rainfall were used in the India experiment. The experiment results could be affected by uncertainties associated with the estimation of rainfall from convective clouds by both of these methods.

Radar estimation of rainfall. Yin et al. (2001) conducted numerical simulations that indicate that hygroscopic seeding can significantly shift the existing rain volume into a narrower distribution of fewer but larger drops and, thereby, alter the radar reflectivity–rainfall (Z–R) relationship. For continental clouds, they found that by using the Z–R relationship for the unseeded clouds to estimate the rainfall from the seeded clouds, an overestimation of as much as 300% in seeding effects can result. Their results also indicated that the overestimates in rainfall caused by hygroscopic seeding of maritime clouds are small since there is little difference in the Z–R relationship between seeded and unseeded clouds.

Mather et al. (1997b), citing the work of Cunning (1976) and Srivastava (1967), argued that seeding may alter the drop size distribution at high levels in the treated clouds, but by the time these drops fall to the levels scanned by radar for measuring rain mass, the drop size distribution will have been readjusted by natural processes. Any differences between seeded and unseeded storm rainfall hydrometeor spectra will, therefore, no longer be detectable. Nissen and List (1998), on the other hand, show that an equilibrium raindrop size spectrum is not attained under conditions of low rain rates.

In both the South Africa and Mexico experiments, the statistical results could be physically explained by the microphysical seeding hypothesis until about 30 min after decision time but could not explain the apparent seeding effect beyond 30 min. This might indicate a dynamic response in the cloud system that carries the effects of seeding beyond the initial production of precipitation. Since most of the storms were seeded within the first 20 min after decision time, it is unlikely that the seeding effects observed beyond 30 min after that time could have been influenced by the problems in radar estimation described by Yin et al. (2001).

Silverman and Sukarnjanaset (1996) were also aware of this potential problem in the radar estimation of rainfall in the Thailand experiment. They made a point of measuring the rain spectra below seeded and unseeded clouds and found that they were fundamentally similar in shape. The rain mass per unit volume in the seeded clouds was greater than that from the unseeded clouds and, when the larger area of the seeded cloud rain shafts were taken into account, the total rain mass produced by the seeded clouds was considerably greater. These findings tended to provide assurance that the radar-estimated increases in rain volume are real.

Although preliminary studies indicate that the hygroscopic seeding did not bias the radar estimation of rainfall by affecting the Z–R relationship in the Thailand experiment, further investigation of this potential problem is, in general, advisable. It is also worthwhile to investigate whether hygroscopic flare seeding and large hygroscopic particle seeding affect the Z–R relationship differently, if at all.

Estimation of rainfall from rain gauges. Silverman et al. (1981) found that, for continental convective storms in the High Plains, the sampling variance associated with a rain gauge density on the order of four rain gauges per convective storm (about 80 km^2 per rain gauge) was responsible for no more than 10% of the total sample size requirement to detect a 25% change in mean precipitation amount due to seeding. The effect of network sampling variance became significant for gauge densities less than one gauge per convective storm. Since the rain gauge densities in the north and south targets were one rain gauge per 44 km^2 and per 47 km^2, respectively, it is likely that sampling variance had an appreciable effect on the estimated rainfall used to evaluate the India experiment.

In future experiments, both radar and rain gauges should be used to estimate rainfall. Brandes (1975) has shown that radar estimates of precipitation are improved when rain gauge observations are used to quantitatively calibrate the radar data. The use of multiple Doppler, and/or airborne Doppler, radar and multiparameter radars can yield more quantitative estimates of rainfall and, in addition, identify possible dynamic seeding signatures.

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