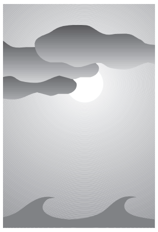
A Critical Assessment of Glaciogenic Seeding of Convective Clouds for Rainfall Enhancement



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ABSTRACT

The scientific evidence for enhancing rainfall from convective clouds by static-mode and dynamic-mode seeding with glaciogenic agents is examined and critically assessed. The assessment uses, as a measure of proof of concept, the criteria for success of any cloud seeding activity that was recommended in the Scientific Background for the 1998 AMS Policy Statement on Planned and Inadvertent Weather Modification, criteria that require both statistical and physical evidence. Based on a rigorous examination of the accumulated results of the numerous experimental tests of the static-mode and dynamic-mode seeding concepts conducted over the past four decades, it has been found that they have not yet provided either the statistical or physical evidence required to establish their scientific validity. Thus, the conclusion of several high-level reviews of weather modification conducted by the Advisory Committee on Weather Control, the National Academy of Sciences, and the Weather Modification Advisory Board during the period from 1957 to 1978 that cloud seeding was promising, unproven, and worth pursuing is still valid today.

The research and experiments related to the static-mode and dynamic-mode seeding concepts, especially those conducted since 1978, provided physical insights about some important cold–cloud precipitation development mechanisms and the possible effect of glaciogenic seeding on them. 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. New experiments are needed to resolve the uncertainties, inconsistencies, and deficiencies in the statistical and physical evidence in support of static-mode and dynamic-mode seeding of convective clouds obtained thus far. Considering the statistically positive result of hygroscopic flare seeding of cold convective clouds in South Africa and its replication in Mexico, and of hygroscopic particle seeding of warm convective clouds in Thailand, efforts to obtain the physical evidence required to place the hygroscopic seeding concept on a secure scientific foundation is, perhaps, a more immediate and higher-priority investment.

Future experiments on glaciogenic seeding of convective clouds, indeed any cloud seeding technique, should feature well-defined physical–statistical tests of the seeding concepts, in accordance with the proof-of-concept criteria, in order to establish their scientific validity. People with water interests at stake who are investing in operational glaciogenic cloud seeding projects for precipitation enhancement should be aware of the inherent risks of applying an unproven cloud seeding technology and provide a means of evaluation that allows for an assessment of the scientific integrity and cost effectiveness of the operational seeding projects. Those who are contemplating investing in operational hygroscopic seeding projects for precipitation enhancement based on the statistically positive experimental results in South Africa, Thailand, and Mexico should be aware that, in the absence of physical evidence required by the proof-of-concept criteria, this cloud seeding technology is also unproven.

1. Introduction

More than 50 years have passed since Schaefer (1946) conducted his historic dry ice seeding demonstration and Vonnegut (1947) discovered the ice nucleating ability of silver iodide, events that ushered in the modern era of weather modification. Field experiments on artificially stimulating rain from convective clouds through glaciogenic seeding (dry ice and silver iodide) began almost immediately (e.g., Kraus and Squires 1947; Leopold and Halstead 1948; Squires and Smith 1949; Smith 1949). Encouraging qualitative results from the early experiments coupled with the ever growing need for additional water supplies led to the

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conduct of more sophisticated, randomized seeding field experiments, cloud model seeding experiments, and the implementation of operational seeding programs over the next 50 years.

The scientific basis for enhancing rainfall from convective clouds by glaciogenic seeding rests on two concepts (Braham 1986). The first concept, commonly called static-mode seeding or seeding for microphysical effects, is based on the postulate that the precipitation efficiency of some clouds,in which precipitation particles originate naturally as ice crystals, is limited by a shortage of natural ice nuclei and that the addition of artificial ice nuclei to these clouds will enhance the amount of precipitation they produce. The second concept, commonly called dynamic-mode seeding or seeding for dynamic effects, is based on the postulate that the seeding-induced conversion of supercooled rain drops into ice particles will result in the production of more rain and stronger downdrafts from the seeded cells which, in turn, will enable the cloud system to grow larger, process more water vapor, and yield even more precipitation.

The purpose of this paper is to critically assess the scientific status of these glaciogenic seeding concepts. This assessment uses, as a measure of proof of concept, the criteria for success of any cloud seeding activity that was recommended in the Scientific Background for the AMS Policy Statement on Planned and Inadvertent Weather Modification (AMS 1998). It is restated here for reference:

> Because the expected effect of cloud seeding is within natural meteorological variability, statistical as well as physical evidence is required to establish the success of any cloud seeding activity. Statistical evidence is most efficiently obtained through a randomized, statistical experiment based on the seeding conceptual model that is conducted and evaluated in accordance with its a priori design, and results in the rejection of the null hypothesis (hypotheses) at an appropriate level of significance and power of detection. The physical plausibility that the effects of seeding suggested by the results of the statistical experiment could have been caused by the seeding intervention, i.e., the physical evidence is consistent with the statistical evidence, must then be established through measurements of key links in the chain of physical events associated with the seeding conceptual model. Physical evidence is essential in confirming the validity of the seeding conceptual model, which provides the basis for transferring the cloud seeding methodology to other geographical areas."

Pursuant to the proof-of-concept criteria, this review is based on a rigorous examination of the accumulated results of numerous experimental tests of the static-mode and dynamic-mode seeding concepts conducted over the past four decades. It focuses primarily on those experiments designed to produce statistical evidence of the efficacy of the seeding concepts and examines the statistical and physical evidence resulting from these experiments. In some ways this review is an update of the review of static-mode seeding of convective clouds by Silverman (1986) and the review of dynamic-mode seeding of convective clouds by Orville (1986). It also elaborates on the glaciogenic seeding aspects of the recent review by Bruintjes (1999) of cloud seeding experiments to enhance precipitation.

2. Statistical assessment criteria

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; and Gabriel 2000). Based on the proof-of-concept criteria, this critical review will, therefore, emphasize the results of randomized statistical experiments conducted and evaluated in accordance with their a priori design as the most credible evidence of seeding effects. 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 analyses whether the reported results do so or not. Several methods of accounting for multiplicity of analyses have been suggested (WMO 1980; Woodley et al. 1982a; and Gabriel 2000). This critical review will use the Bonferroni method (see Gabriel 2000; Silverman and Sukarnjanaset 2000), whereby the statistical level of significance is shared equally among the number of hypotheses/analyses indicated. It is emphasized that failure to reject any null hypothesis does not connote that seeding is ineffective; rather, it simply means that the evidence was insufficient to establish that seeding worked as hypothesized. A statistically insignificant result with a test statistic [e.g., single area seed/no-seed ratio (SR)] greater than unity is not and should not be interpreted as a positive effect of seeding any more than a SR value less than unity is not and should not be interpreted as a negative effect of seeding.

Exploratory analyses and reanalyses of various glaciogenic cloud seeding experiments will also be discussed. In accordance with the guidance provided by statisticians to the weather modification community referenced above, the reader is cautioned that *P* values associated with exploratory analyses cannot be used to reject null hypotheses as is the case for analyses specified a priori; however, following the lead of Mather et al. (1997) they will be cited in this review as an indication of the strength of suggested effects that can only be confirmed through new, a priori experiments specifically designed to establish their validity. How small a *P* value has to be before an exploratory result is considered strong enough to be taken seriously (as "encouraging" or "promising") is not generally defined but, in view of the problem of multiplicity of analyses. conventional wisdom dictates that it must be considerably smaller than the *P* value of 0.05 usually associated with the rejection of a null hypothesis in an a priori evaluation.

The account of glaciogenic seeding activities does not include a discussion of operational, nonrandomized seeding projects and the results of their analyses. Rigorous evaluation based on probabilistic tests of significance requires the treatment allocation to have been randomized. Gabriel and Petrondas (1983) have shown that reliable conclusions cannot be drawn from comparisons of operational data with historical records, and have demonstrated the biases encountered in trying to do so. Because of these biases, they suggest that *P* values from analyses of this type should be roughly doubled.

3. Static-mode seeding experiments

Since the early 1960s, the scientific status of static-mode seeding of convective clouds for rainfall enhancement has been inextricably linked to the findings and results of the Israeli cloudseeding experiments. Whereas other experiments such as HIPLEX-1 (Smith et al. 1984; Mielke et al. 1984; Cooper and Lawson 1984) and the Australian experiments (Ryan and King 1997) failed to verify the static-mode seeding concept, the results of the Israeli cloud seeding experiments (Gagin and Neumann 1974, 1981) were perceived initially as supporting it. This assessment will, therefore, focus on the results of these experiments as a measure of the scientific status of static-mode seeding of convective clouds for rain enhancement.

a. Statistical evidence

1) The Israel-1 experiment

The Israel-1 cloud seeding experiment (Gagin and Neumann 1974) was conducted during the period 1961–67. It was designed as a randomized crossover experiment with north and center target areas separated by a buffer zone. Each day was randomly allocated for seeding in either the north or center target area with the nonseeded area acting as control for the seeded area. Seeding was accomplished by dispersing silver iodide smoke from an airplane at cloud-base level, parallel to the coastline upwind of the randomly selected target area. The root-double ratio (RDR) test statistic (Gabriel 1999) was used in evaluating the experiment. The evaluation yielded an RDR of 1.15, that is, a suggested rain enhancement of 15%, with a one-sided *P* value of 0.009 for the combined targets. It was found through exploratory analysis that the apparent rain increase peaked in the interior part of the targets located 25–50 km downwind of the seeding line, yielding a suggested rain increase of 22% for the combined targets with a one-sided *P* value of 0.002. Exploratory analyses of the north and center targets separately were also conducted (Neumann and Shimbursky 1972; Gagin and Neumann 1974). The SR for the north and center target areas was 1.15 and 1.16, respectively, with associated one-sided *P* values of about 0.16 for both target areas.

2) The Israel-2 experiment

The Israel-2 cloud seeding experiment (Gagin and Neumann 1981) was conducted during the period 1969–75 as a randomized crossover experiment with north and south target areas separated by a buffer zone. The center target in Israel-1 was extended far to the south to form the south target for Israel-2, nearly doubling its area. As in the Israel-1 experiment, each day was randomly allocated for seeding in either the north or south target area with the nonseeded area acting as control for the seeded area.

Gagin and Neumann (1981) stated that the Israel-1 experiment was based on several working hypotheses and its exploratory results formed the basis of the "confirmatory" Israel-2 experiment. They reported that a primary purpose of Israel-2 was to enhance rainfall through seeding in the Lake Kinneret catchment area that serves as the principal reservoir of the Israel National Water Carrier. Therefore, the seeding line for the north target was shifted inland in an attempt to focus the maximum seeding effect on the catchment area. This created an upwind control area for the north target allowing a target-control evaluation of seeding effects on the north target alone. The seeding line for the south target was on the coastline as before. A network of ground generators was installed in the north and south target areas to supplement the aircraft seeding.

Using the double ratio (DR) statistic (Gabriel 1999), Gagin and Neumann (1981) indicated that the rainfall in the north target area was increased by 13% with a one-sided *P* value of 0.028. The largest seeding effect in the North target was found over the catchment area of Lake Kinneret where the suggested rainfall increase was 18% with a one-sided *P* value of 0.017. An exploratory analysis of the north and south targets separately by Gabriel and Rosenfeld (1990) indicated a 15% increase in rain with a two-sided *P* value of 0.23 and a 17% decrease in rain with a two-sided *P* value of 0.15, respectively. The single ratio evaluation of the Lake Kinneret catchment and south-central areas, separately, yielded similar results.

3) The Israel-3 experiment

A third randomized experiment (Israel-3) was launched in 1975 that was designed to evaluate the seeding effect on the south alone. The south target area of Israel-2 became the primary target of Israel-3, excluding its southwest corner that was designated as an upwind control area to facilitate this evaluation. An intermediate analysis was done for 682 experimental days in the period November 1976–April 1991 (Nirel and Rosenfeld 1994). Based on a DR statistic, a 4.5% decrease in rainfall with a two-sided *P* value of 0.42 was indicated; therefore, they concluded that no seeding effect on rainfall was indicated in the south target area.

b. *Physical evidence*

HIPLEX-1 and the Israeli experiments used different approaches in their attempts to provide substantiation of the physical hypothesis underlying static-mode seeding of convective clouds for rainfall enhancement. In HIPLEX-1, the experimental design was based on a detailed seeding conceptual model, and the quantitative physical measurements required to verify it were incorporated as an integral part of the experiment. The Israeli experiments, on the other hand, were "black-box" experiments, that is, the clouds were seeded with the silver iodide particles and the primary variable measured and analyzed was the precipitation on the ground (Cotton 1986). The Israeli experiments were based on a general conceptual model that evolved from previous physical studies of clouds and cloud systems in the experimental area, and the experimental results were analyzed for their physical plausibility within stratifications of the experimental data. Gagin (1986) acknowledged that the Israeli approach was riskier than the approach used in HIPLEX-1 because of the complexity in making sound physical hypotheses on the basis of circumstantial scientific evidence only; however, he justified its use on the grounds that it required less human and equipment resources. and had the potential of providing quicker answers at a reduced cost under favorable conditions. Just how much riskier the Israeli approach turned out to be will become evident in the sections to follow.

1) HIPLEX-1

HIPLEX-1 (Smith et al. 1984) was a randomized experiment that was specifically designed to test the static-mode seeding concept for enhancing rainfall from convective clouds. It specified in advance and attempted to verify by observations each step in the chain of physical events leading to additional precipitation at cloud base. Semi-isolated cumulus congestus clouds were seeded by dropping a line of dry ice pellets from a jet aircraft at a rate of 0.1 kg km^{-1} near the −10°C level within 2 min after a suitable cloud was selected. A total of 20 cases were obtained during the 2-yr tenure of the program, 12 seeded and 8 not seeded. The statistical results (Mielke et al. 1984) showed that the postulated increases in cloud ice concentrations associated with seeding and the subsequent onset of riming were unequivocally established despite the limited data sample. Beyond 5 min after treatment, it was found that most of the clouds were not behaving as expected.

The physical evaluation (Cooper and Lawson 1984) revealed that in 4 of the 12 seeded clouds precipitation developed in the hypothesized manner, but physically significant departures occurred in the other 8 clouds. It was found that 1) in general, the liquid water depleted faster by entrainment than seeding could exploit it to develop precipitation; 2) precipitation development did not proceed via the graupel process as hypothesized in most of the seeded clouds—rather, the dominant precipitation process was a combination of aggregation and low-density accretion onto the loose aggregates presumably due to the high concentrations of ice crystals produced by the seeding; and 3) precipitation development proceeded as hypothesized in the few clouds with sustained updrafts but, even then, the choice of seeding level was perhaps too low since it failed to take advantage of the region of rapid development of graupel from ice crystals at about the –12° and –20°C temperature levels.

Because of the experimental approach, the complementary physical evaluation was able to identify where, how and why the seeded clouds behaved differently than postulated by the static-mode seeding hypothesis. This phase of the experiment was, therefore, terminated and the Cooperative Convective Precipitation Experiment was launched in order to gain an improved understanding of convective clouds, especially those larger than the ones treated in HIPLEX-1 (Knight 1982).

2) The Israeli experiments

According to Gagin (1981) physical plausibility of the results of the Israeli experiments rests on statistical analyses of the rainfall data that confirm the microphysical predictions based on the general conceptual model that evolved from previous field studies. Previous field studies indicated that continental clouds over Israel exhibit high colloidal stability as indicated by the narrowness of the cloud droplet spectra and the apparent inefficiency of the collision–coalescence mechanism at the droplet sizes observed. From these observations, Gagin and Neumann (1974) concluded that ice crystals are essential for the formation of precipitation in these clouds and this, coupled with the absence of ice crystal multiplication mechanisms, formed the basis for cloud seeding with glaciogenic seeding agents in Israel.

Gagin (1981) stated that the most physically significant result of the Israeli experiments was the statistical exploratory analyses of the data stratified according to cloud-top temperature. The largest seeding effect with the smallest *P* value was found in the cloud-top temperature stratification of –15° to –21°C, the temperatures at which seeding should be most effective according to the general conceptual model. For both warmer and colder cloud-top temperature stratifications the magnitudes of the seeding effect decreased and their *P* values increased. As additional physical evidence Gagin (1981) stated that known patterns of turbulent diffusion of the seeding material released at cloud-base altitudes was sufficient to explain the finding that maximum seeding effect was consistently found 30–50 km downwind of the seeding line. He concluded that these studies, while far from being complete, provide a fair basis for understanding and accepting the statistical results and thus also indicate which criteria should be used to transfer the static-mode seeding technique to other geographical areas.

c. *Reanalyses and alternative explanations*

Gabriel and Rosenfeld (1990) reanalyzed Israel-2 as a randomized crossover (north vs south) experiment, asserting that the experiment was designed and conducted with this as well as the north target-control analysis (Gagin and Neumann 1981) intended. Indeed, Gagin and Neumann (1974) analyzed the first 2 yr of Israel-2 as a randomized crossover experiment. Gabriel and Rosenfeld (1990) used the RDR as the test statistic, as was done for Israel-1, and obtained a 2% decrease in rainfall with a two-sided *P* value of 0.64; there was no apparent effect on the rainfall in the combined targets. Applying the crossover RDR analysis to the Lake Kinneret catchment area in the north (which was targeted for maximum effect) and the central area in the south, a 2% decrease in rain with a two-sided *P* value of 0.67 was obtained. In an effort to discover if there was a suggestion of seeding effects on the individual targets, especially in light of the results of Israel-1, they conducted a series of exploratory analyses. In particular, they examined the evidence with regard to three possible alternative hypotheses: 1) N_0S_0, seeding had no effect on either the north or south target; 2) N_+S_0, there was a positive effect of seeding in the north and no effect in the south; and 3) N_+S_-, there was a positive effect of seeding in the north and a negative effect of seeding in the south. While there was some evidence in support of all three hypotheses, they concluded that the weight of the evidence, while not conclusive, tended to favor the third hypothesis, N_+S_-. The results of Israel-1, on the other hand, supported the hypothesis, N_+C_+, a positive effect of seeding in both the north and center targets.

Rosenfeld and Farbstein (1992) sought to explain the ineffectiveness of seeding in the south by proposing a desert-dust hypothesis. They postulated that desert dust, advected from the North African, Sinai and Negev Deserts, acting as ice nuclei and/or giant cloud condensation nuclei (sulfate-coated desert dust as shown by Levin et al. 1996), seeded the clouds in the south (and to a much lesser degree in the north), thereby negating the effect of the silver iodide seeding particles. Studies by Levi and Rosenfeld (1996) and Rosenfeld and Nirel (1996) provide some support for the desert-dust hypothesis. On the other hand, Levin et al. (1997) suggested that seeding was less effective in the south because the effective concentration of silver iodide particles at activation temperatures was much lower than it was in the north. Using a three-dimensional mesoscale model, they simulated the seeding operation in the Israel experiments and the resulting dispersal of the seeding particles. They found that high concentrations of seeding particles were removed from the atmosphere by downdrafts below the clouds in the south, resulting in seeding particle concentrations at activation temperatures that were about one-third that obtained in the north.

Rangno and Hobbs (1995) challenged the statistical results of both the Israel-1 and Israel-2 experiments, and the appropriateness of the static-mode seeding concept upon which these experiments were based. They claimed that the positive finding of Israel-1 was the result of a type-1 error (that is, a false positive or a "lucky draw"). They based this claim mainly on the results of the analysis by Wurtele (1971) that showed that the single ratio of the rainfall in the buffer zone during center-seeded days was even larger than that indicated for the center target area. Since a wind analysis (Wurtele 1971) indicated that it was unlikely that this could have occurred as a result of contamination from the seeding in the center target area, they argued that the single ratio for the center target area and, therefore, the crossover experiment were the result of a lucky draw and not seeding. Assuming that the lucky draw would, due to the nature of the crossover design, cause the seeding effect in the north target area to be underestimated, Rosenfeld (1997) adjusted the single ratios of the rainfall in the north and center target areas by the amount indicated for the single ratio of the rainfall in the buffer zone. By doing this, the RDR for the combined targets was unchanged but the north target single ratio was now much greater than unity and the center target single ratio was now slightly less than unity. Rosenfeld (1997) pointed out that the sense of the adjusted results for Israel-1 was now consistent with that of Israel-2 whereas the original Israel-1 results were not. An examination of the distribution of rainfall in the target areas and buffer zones as well as the areas surrounding them led Rangno and Hobbs (1995) to suggest that the results of Israel-2 were also compromised by a type-1 statistical error; however, they (Rangno and Hobb 1997) did admit that the chances of lucky draws occurring in both the Israel-1 and Israel-2 experiments were very slim.

Citing the results of analyses of the precipitation climatology of Israel and measurements of the microstructure of Israeli clouds by Levin (1992), Rangno and Hobbs (1995, 1997) showed that convective clouds in Israel produce large cloud droplets, precipitation-sized drops, high concentrations of ice crystals, and precipitation at relatively warm cloud-top temperatures, all of which are not consistent with the physical criteria for applying the static-mode seeding concept.

d. *Attempts at transferability*

The apparent success of the Israeli experiments prompted two unsuccessful attempts to transfer the Israeli seeding technique and, hopefully, its results to other places in the world, namely the World Meteorological Organization Precipitation Enhancement Project (WMO PEP) experiment in Spain (WMO 1986) and the Puglia experiment in Italy (List et al. 1999).

1) The WMO PEP experiment

In the case of Spain, the WMO selected the static-mode seeding concept as the scientific basis for PEP. Clouds were considered to be seedable for increasing precipitation according to the static-mode seeding concept if 1) the collision–coalescence process is inefficient, 2) the rate of formation of supercooled condensate exceeds or is comparable to the rate of depletion of supercooled water, and 3) if there is sufficient time to grow seeding-induced precipitation particles that can reach the ground. Unfortunately, the WMO prematurely terminated PEP field studies because of fiscal constraints. Field studies were terminated after three seasons of site selection studies, before it could be determined whether seedable conditions occurred frequently enough according to the static-mode definition of seedability to warrant the conduct of a statistical seeding experiment. It was found that the seedability criteria specified by the static-mode definition was difficult to apply practically because of its lack of quantification.

2) The Puglia experiment

The Puglia experiment was designed to test the transferability of the Israeli cloud seeding technology to the meteorology and geography of Puglia, Italy. It was carried out during 1988–94 as a black-box replication of the Israeli cloud seeding technology. It was designed as a randomized crossover rain enhancement experiment with two alternating target areas (Bari and

Canosa), a buffer zone between them, and two additional control areas. Seeding was accomplished by injection of silver iodide into clouds by aircraft flying near the bases of clouds along predetermined tracks upwind of each target area. Israeli scientists, pilots and seeding aircraft were imported to ensure transferability of the seeding technology. Evaluation of the Puglia experiment by List et al. (1999) indicated no statistically significant effect of seeding; the RDR was 0.92 (a suggested decrease of 8%) with a two-sided *P* value of 0.35. Exploratory analyses suggested that the clouds over the Bari and Canosa target areas may have been different and that the Bari target might have responded more favorably to seeding under intermediate moisture conditions. Without any physical measurements and/or modeling accompanying the seeding experiment, List et al. (1999) were unable to establish the physical plausibility of this or any other exploratory suggested effect of seeding. Indeed, they were not able to check whether the static-mode seeding concept was even applicable to the Puglia clouds and justified the Israeli cloud seeding technology that was used.

4. Dynamic-mode seeding experiments

Observations of dynamic effects following glaciogenic seeding were first reported by Kraus and Squires (1947) in their experimental seeding of large, supercooled cumulus clouds with dry ice in Australia. They reported one case in which a cumulus cloud with a cloud-top height of 23 000 ft was seeded with 150 lb of dry ice, whereupon it grew spectacularly to 40 000 ft in 13 min. Within 5 min after seeding, the cloud produced a radar echo and heavy rain. Langmuir (1951), Vonnegut and Maynard (1952), and Orr et al. (1950) observed similar occurrences of rapid growth after seeding.

Quantitative testing and development of the dynamic-mode seeding concept began in 1963 under the aegis of the joint Navy–Environmental Science Services Administration Project Stormfury cumulus program (Simpson et al. 1967). This was followed by a series of randomized seeding experiments in Florida, Texas, Cuba, and Thailand. This assessment will follow the evolution of the dynamic cold-cloud seeding conceptual model from experiment to experiment chronologically and, in particular, critically examine the statistical and physical evidence of its efficacy.

a. *Statistical evidence*

1) The Caribbean experiment

During the summer of 1965, a randomized cloud seeding experiment was carried out on individual tropical cumulus clouds over the Caribbean Ocean (Simpson et al. 1967). A total of 23 clouds were selected, 14 of which were seeded and 9 were studied as controls. Seeding was accomplished by an aircraft that dropped from 8–16 pyrotechnic silver iodide flares, each flare releasing 1.2 kg of silver iodide smoke, into the top of the growing cumulus cloud. The experiment was designed to test the effect of seeding on cumulus growth and to test the skill of a one-dimensional, steady-state model (called EMB 65) to predict it. Cloud growth was documented by means of aircraft, radar, and photogrammetric observations. No attempt to test the effect of seeding on rainfall was made during the experiment. The analysis of the experiment showed that the seeded clouds increased in height 1.6 km more following treatment than did the control clouds, the difference being significant at the 0.01 level, and that the cloud model predicted with remarkable skill the amount of growth and the conditions required for it.

2) The Florida experiments

(i) South Florida 1968 (SF68)

The first of four randomized, convective cloud seeding experiments based on the dynamic-mode seeding concept was carried out in south Florida during May 1968 (Woodley 1970). As in the Caribbean experiment, the SF68 experiment was a single cloud experiment. Nineteen clouds were selected for treatment, 14 of which were seeded and 5 were unseeded (controls). There were also five radar controls, that is clouds selected after the fact on a nonrandom basis by a knowledgeable but uninvolved scientist who judged them to fulfill the visual eligibility criteria for experimental clouds by viewing nose camera films taken by the seeder aircraft. These clouds were then located on the radar films and analyzed along with the treated clouds. Each of the seeded clouds received 1 kg of silver iodide smoke from twenty 50-g silver iodide pyrotechnics that were dropped into the cloud from an aircraft flying at approximately 6.1-km above mean sea level. The purpose of the seeding was twofold: to alter the cloud dynamics and to increase precipitation as a by-product of the dynamic alteration. An aircraft that flew just above the visual cloud top measured the height of the clouds randomly selected for treatment.

It was found that the average growth difference between seeded and unseeded clouds was 3.5 km, with a P value of 0.005. Many analyses of the radar-estimated rainfall from the seeded and unseeded clouds were conducted, with and without the radar controls. The analysis of radar-estimated rainfall 40 min after the treatment pass (R_{40}) indicated that the average rainfall of the seeded clouds was more than double that of the unseeded clouds (not including the radar controls), the SR was 2.16 with the two-sided P value being somewhat less than 0.20. When the radar controls were included in the sample of unseeded clouds, the SR was 2.44 and the two-sided P value was somewhat less than 0.10.

(ii) South Florida 1970 (SF70)

The 1968 randomized, single cloud seeding experiment (SF68) was repeated in 1970 (Simpson and Woodley 1971). Design changes were made in an effort to improve the cloud selection and treatment operations. Nineteen single clouds were selected for treatment, 13 of which were seeded and 6 were unseeded (controls). There were also 10 radar controls. As in SF68, an aircraft that flew just above the visual cloud top measured the height of the clouds randomly selected for treatment. It was found that the average growth difference between seeded and unseeded clouds was 1.9 km, with a P value of 0.01. Again many analyses of the radar-estimated rainfall from the seeded and unseeded clouds were conducted, but only with the nonrandomly selected radar controls included. The analysis of radar-estimated rainfall 40 min after the treatment pass (R_{40}) indicated that the SR, that is, the S/NS ratio of average rainfall of the seeded clouds to the unseeded clouds with radar controls included, was 1.57 with a one-sided P value of 0.10. A similar analysis of the radar-estimated rainfall over the total cloud lifetime after seeding (R_{LT}) yielded a SR of 2.80 with a one-sided P value of 0.05.

(iii) FACE-1

The first Florida Area Cumulus Experiment (FACE-1) was carried out in south Florida from 1970 to 1976 (Woodley et al. 1982b). It was a single-area, randomized, exploratory experiment to investigate whether seeding convective clouds according to the dynamic-mode seeding concept could enhance precipitation over a substantial area. Seeding was accomplished by an aircraft dropping pyrotechnic flares of 50–70 g each into the tops of convective towers, which satisfied both visual and measurement criteria. The primary response variables were rain gauge–adjusted, radar estimates of rainfall in the total target (TT) and in the floating target (FT), the most intensely treated portion of the target. During the course of the experiment a number of important design changes were made, some based on economic necessity and some as a result of new information.

There were 104 days of experimentation, 53 seed and 51 no seed. Of these, 29 (14 seed and 15 no seed) are so-called A days and 75 (39 seed and 36 no seed) are so-called B days. The B days are days on which the clouds received 60 flares or more and, according to Woodley et al. (1982b), compose the dataset to which the FACE conceptual model best applies. The A days are days on which clouds received less than 60 flares because the flight scientist decided that the target suitability criteria were no longer satisfied. A rerandomization analysis of the rainfall in the 6-h (360 min) period after treatment (R_{360}) for the B days yielded SR values of 1.49 with a one-sided P value of 0.01 and 1.23 with a one-sided P value of 0.08 for the FT and TT, respectively. For the combined A and B days, the rerandomization analysis yielded SR values of 1.46 with a one-sided P-value of 0.03 and 1.29 with a one-sided P-value of 0.05 for the FT and TT, respectively. A linear model analysis of the data was carried out in an attempt to take into account some of the natural rainfall variability and this resulted in somewhat larger point estimates of the seeding effect with somewhat stronger P-value support than did the rerandomization analyses.

(iv) FACE-2

FACE-2 was carried out during the summers of 1978, 1979, and 1980 (Woodley et al. 1983). Whereas FACE-1 was an exploratory experiment, FACE-2 was designed and conducted as a confirmatory experiment. It attempts to confirm the principal seeding effects in FACE-1 in accordance with clarified and sharpened confirmatory specifications provided by Woodley et al. (1982a), and to replicate the main analyses of FACE-1. Three levels of confirmation, ordered from weakest to strongest, were specified as follows:

The first and weakest level of confirmation—The adjusted P value (adjusted for multiplicity of analyses) for the set of two double ratios of S/NS rainfall in the 2–5-h (120–300 min) period after treatment, $R_{120-300}$, to the S/NS rainfall in the 2-h (120 min) period after treatment, R_{120}, on B days, one double ratio for the FT and one double ratio for the TT, has substantial probability support.

The second and somewhat stronger level of confirmation—The adjusted P value for the set of two double ratios in the first level of confirmation plus the two single ratios of S/NS rainfall in the 6-h (360 min) period after treatment R_{360}, on B days, one single ratio for the FT and one single ratio for the TT, has substantial probability support.

The third and strongest level of confirmation—The adjusted P value for the set of two double and two single ratios in the second level of confirmation plus the two single ratios of S/NS rainfall in the 6-h period after treatment, R_{360}, on A+B days, one single ratio for the FT and one single ratio for the TT, has substantial probability support.

To account for multiplicity of analyses, the adjusted P value for the set of test statistics at each level of confirmation was obtained by multiplying the minimum P value in the set by the number of test statistics in the set (2, 4, and 6 test statistics for the first, second, and third level of confirmation, respectively).

FACE-2 failed to confirm the findings of FACE-1 at the first and weakest level of confirmation since the P values for the FT and TT double ratios even before accounting for multiplicity were 0.78 and 0.81, respectively. This precluded moving on to the next strongest levels of confirmation according to the confirmatory specifications. FACE-2 also failed to replicate the main analyses of FACE-1. The FACE-2 rerandomization analysis of rainfall in the 6-h period after treatment, R_{360}, on the B days yielded SR values of 1.08 with a one-sided P value of 0.42 and 1.04 with a one-sided P value of 0.45 for the FT and TT, respectively. The rerandomization analysis of the rainfall in the 6-h period after treatment, R_{360}, on A and B days combined yielded SR values of 1.21 with a one-sided P value of 0.30 and 1.03 with a one-sided P value of 0.45 for the FT and TT, respectively. The linear model analysis of the data yielded equally disappointing results.

3) The Texas experiment

The Texas randomized seeding experiment was carried out under the Southwest Cooperative Program (SWCP) over an area centered on Big Spring, Texas, during the years 1986, 1987, 1989, 1990, and 1994 (Rosenfeld and Woodley 1989, 1993; Woodley and Rosenfeld 1996). It was designed to test the effect of seeding with droppable silver iodide flares on mesoscale convective clusters (experimental units) and the treated convective cells (treatment units) in the experimental units. Rosenfeld and Woodley (1993) stated "it is the cell that receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen on the experimental unit that contains the cells." In order to obtain the best representation of the full life cycle of the cells, including the mature and dissipating stages, a long-tracking algorithm was used in addition to the short-tracking algorithm of Rosenfeld (1987). In long-tracking, cell tracking is continued (forced) through all mergers and splits and is terminated only after it is determined that the cell is dying, as quantified by the relationship of its current properties to its historical maximum. Rosenfeld and Woodley (1989) indicated that the cell long-tracking procedure occasionally produced cells with duplicate histories in the latter portion of their life, and cautioned that this may create problems in applying rigorous statistical procedures to the long-track cell data.

Over the duration of the Texas experiment a total of 38 experimental units (18 S and 20 NS) were obtained. The analysis of individual cells was limited to 28 experimental units (13 S and 15 NS) because the quality of the radar data in 1986 did not permit radar cell tracking analyses. The 28 experimental units contained 213 long-track cells (99 S and 114 NS) and 209 short-track cells (97 S and 112 NS). The evaluation of the Texas experimental data (Woodley and Rosenfeld 1996) included many analyses, yielding the following main results: 1) the SR values for the maximum height of the treated long-track convective cells, H_{LTC}, and short-track convective cells, H_{STC}, was 1.10 with a rerandomization P value of 0.21 and 1.00 with a rerandomization P value of 0.47, respectively; 2) the SR values for the radar-estimated rainfall from treated long-track convective cells, R_{LTC}, and short-track convective cells, R_{STC}, was 2.63 with a rerandomization P value of 0.014 and 1.69 with a rerandomization P value of 0.04, respectively; and 3) the SR for the experimental unit radar-estimated rainfall in the 150 min after qualification, R_{150}, was 1.45 with a rerandomization P value of 0.16.

4) The Cuba experiments

A randomized seeding experiment on tropical convective clouds was conducted in the Camaguey area of Cuba from 1985 to 1990 (Koloskov et al. 1996). The purpose of the experiment was to assess the capability of cold-cloud seeding with silver iodide pyrotechnics to augment radar-estimated rainfall from individual convective clouds and convective cell clusters over Cuba.

The Cuba experiment was carried out in two steps. An exploratory experiment was carried out in 1985 in order to determine the type of convective clouds that responded best to seeding. A total of 46 convective clouds, 29 seeded and 17 unseeded, were studied. An analysis of these data indicated that clouds thought to be most suitable for seeding were optically dense growing clouds whose tops at the time of treatment had risen to at least the height of 6–8 km (cloud-top temperatures between −10° and −20°) and have cloud-top diameters between 2 and 5 km. Seeded clouds meeting these criteria appeared to grow taller, live longer, and produce more radar-estimated rainfall than their unseeded counterparts.

A confirmatory phase of the experiment was carried out during 1986–90 on both individual convective clouds and mesoscale cloud clusters, which will be referred to here as the Cuba-1 and Cuba-2 experiments, respectively. The analysis focused on the effects of seeding on the radar-estimated properties of both the individual convective clouds and mesoscale cloud clusters for the total cloud sample and the subset of clouds that the exploratory experiment indicated was most suitable for seeding, that is the subset with echo top heights between 0.65 and 8.0 km at the time of treatment. A cell short-tracking methodology similar to that of Rosenfeld (1987) was developed to derive the values of six radar-estimated cloud properties including rain volume (R), maximum echo top height (H), maximum radar reflectivity (Z), maximum echo area (AM), total integrated echo area (AI), and echo duration (T). A statistical evaluation of the differences between the average seeded and unseeded values of these six radar-estimated cloud properties was made using the Mann–Whitney two-sample test.

(i) Cuba-1

A total of 46 individual convective clouds, 24 seeded and 22 unseeded, were obtained. The analysis of these clouds indicated that the SR for T, R, H, and AI was 1.11, 1.41, 1.04, and 1.31, respectively, with P values of 0.21, 0.22, 0.77, and 0.18, respectively. The SR value for Z and AM was 1.03 and 1.20, respectively, but no P values were given. Of the total sample of clouds, 20 individual convective clouds, 11 seeded and 9 unseeded, were in the category that the exploratory experiment indicated was most suitable for seeding. The results of the analysis of this subset of clouds (designated as such by adding the suffix 68 to the radar-estimated cloud property symbols) indicated that the SR for $T68$, $R68$, $H68$, AI68, $Z68$, and AM68 was 1.24, 2.22, 1.08, 1.64, 1.05, and 1.38, respectively, with P values of 0.07, 0.07, 0.49, 0.10, 0.23, and 0.20, respectively.

(ii) Cuba-2

A total of 82 mesoscale cloud clusters, 42 seeded and 40 unseeded, was obtained. The analysis of these cloud clusters indicated that the SR for T, R, H, and AI was 1.15, 1.43, 1.08, and 1.19, respectively, with P values of 0.03, 0.04, 0.06, and 0.07, respectively. The SR value for Z and AM was 1.00 and 1.07, respectively, but no P values were given. Of the total sample of clouds, 42 mesoscale cloud clusters, 19 seeded and 23 unseeded, were in the category that the exploratory experiment indicated was most suitable for seeding. The results of the analysis of this subset of cloud clusters indicated that the SR for $T68$, $R68$, $H68$, AI68, $Z68$, and AM 68 was 1.21, 1.65, 1.17, 1.33, 1.01, and 1.28, respectively, with P values of 0.04, 0.02, 0.01, 0.03, 0.84, and 0.05, respectively.

5) THE THAILAND EXPERIMENT

A randomized, cold-cloud, rain enhancement experiment was carried out during 1994–98 in the Bhumibol catchment area in northwestern Thailand to determine the potential of on-top AgI seeding to enhance area (over 2000 km^2) rainfall (Woodley et al. 1999a). This confirmatory experiment was encouraged by the results of exploratory experiments conducted in 1991 and 1993, which indicated that the ratio of the average rainfall from 8 seeded experimental units to that of 7 unseeded experimental units 300 min after unit qualification was 2.73 (Silverman et al. 1994), a suggested increase in rainfall due to seeding of 173%. The confirmatory experiment was conducted in accordance with a formal, randomized, floating-target design patterned after the one used in the Texas experiment. The treatment units were vigorous supercooled clouds forming within the experimental unit, a circle having a radius of 25 km and centered at the location of the convective cloud that qualified the unit for initial treatment. The unit floated with the wind as the S-band project radar collected 5-min volume-scan data to be used for the evaluation of cell and unit properties. The experimental procedures for unit qualification and its treatment were specified in advance (Woodley et al. 1999a, 1999c).

The Thai cold-cloud experiment obtained 62 experimental units, 31 S and 31 NS, that satisfied the qualification criteria specified in the a priori design. The ratio of S to NS radar-estimated unit rainfall in the 5 h (300 min) after unit qualification, R_{300}, was 1.48 with a one-sided P value of 0.11 (Woodley et al. 1999b, 1999c; Woodley and Rosenfeld 2000). The 62 experimental units were composed of 642 long-track cells (353 S and 289 NS). An analysis of the cell data by this reviewer indicated that the SR for the radar-estimated rainfall for the life of the long-track cells after unit qualification, R_{LTC}, was 1.35 with a one-sided P value of 0.11.

Woodley et al. (1999b,c) also conducted a number of exploratory analyses using all the experimental units obtained during the course of the exploratory and confirmatory phases of the experiment in order to assess whether it was possible that seeding had any effect on the clouds and their rainfall production. The exploratory analysis sample consisted of 85 experimental units (43 S and 42 NS). It included the 15 experimental units (8 S and 7 NS) qualified during the exploratory phase of the experiment and 8 experimental units (4 S and 4 NS) qualified during the confirmatory experiment that met a qualification criterion for liquid water content that was relaxed after the experiment was underway. The exploratory evaluation of the accumulated rain volume in the experimental units 300 min after qualification, R_{300}, yielded a SR of 1.58 with a P value of 0.05 and for 600 min after qualification, R_{600}, it yielded a SR of 1.91 with a P value of 0.03. These results were undoubtedly biased by the very favorable results produced by the 15 experimental units qualified during the exploratory phase of the experiment, results that were used to justify undertaking the confirmatory experiment. The 85 experimental units were composed of 850 long-track cells (461 S and 389 NS). The analysis of the maximum long-track cell height, H_{LTC}, and radar-estimated long-track cell rainfall, R_{LTC}, was 1.03 with a one-sided P value of 0.28 and 1.36 with a one-sided P value of 0.07, respectively (Woodley et al. 1999b; Woodley and Rosenfeld 2000).

b. Physical evidence

All of the dynamic-mode seeding experiments can be regarded as black-box experiments. All of them were based primarily on radar-derived properties of the cloud entities being studied. None of the statistical experiments were accompanied by systematic measurements of the key links in the chain of physical events associated with the dynamic-mode seeding conceptual model, as required to establish physical plausibility. Physical measurements were made; however, they consisted of small samples taken under conditions of high cloud-to-cloud variability. Many of the physical measurements were not taken in the clouds that were randomly selected for treatment during the experiments (see, e.g., Woodley and Rosenfeld 2000). It was claimed that the results of the supporting physical studies were relevant to and consistent with the dynamic cold-cloud seeding conceptual model as postulated at that time (see, e.g., Rosenfeld et al. 1999).

The physical support for the dynamic-mode seeding conceptual model comes from such studies as 1) the microphysical study by Sax et al. (1979) that showed that clouds seeded with silver iodide contained more ice than their unseeded counterparts; 2) the theoretical study by Lamb et al. (1981) that indicated that dynamic seeding should work best in clouds that contain rain drops; 3) the radar studies by Gagin et al. (1985) and Gagin et al. (1986) specified the relationship between maximum echo heights and the rain volumes produced by individual convective cells and showed that an increase in cell-top height nearly doubles its rain production; 4) the radar study by Rosenfeld and Woodley (1993) that suggested that seed convective cells merge with neighboring cells more frequently than unseeded convective cells; 5) the exploratory analyses of Woodley and Rosenfeld (1996) that suggested that the apparent effects of seeding were larger in clouds with cloud-base temperatures ≥ 15°C, which they attributed to the greater likelihood that rain drops would be present in vigorous updrafts above the freezing level because of more active condensation–coalescence processes; 6) the microphysical study by Rosenfeld and Woodley (1997) that suggested that the initial response of the cloud to dynamic seeding is greatest in clouds that contain supercooled rain drops; 7) the microphysical studies by Sudhikoses et al. (1998) and Rosenfeld et al. (1999) that indicated that the supercooled liquid water content depletes faster in seeded clouds than in unseeded clouds; and 8) the microphysical study by Woodley and Rosenfeld (2000) that suggested that seeding appears to result in the production of ice in invigorated updraft regions with a concomitant decrease in the cloud water. The numerical model experiments of seeding cold convective clouds with ice nuclei by Reisen et al. (1996) showed, on the other hand, that seeding effectiveness was greatest in extreme continental clouds, in which collision–coalescence played only a minor role, and decreased as the clouds became less continental in character until it was only marginally effective for maritime clouds.

5. Critical assessment

As described in sections 3 and 4, a large number of static-mode and dynamic-mode cold-cloud seeding experiments have been conducted. They have yielded an even larger number of statistical analyses of the S/NS ratio of rainfall and many other radar-estimated cloud properties, and some supporting physical studies. The results of these statistical analyses and physical studies will now be put into perspective by evaluating them in the context of the proof-of-concept criteria that were enunciated at the outset of this assessment.

a. *Static-mode seeding*

1) STATISTICAL EVIDENCE

For ease of reference, the statistical results of the Israeli static-mode seeding experiments discussed in section 3 are summarized in Table 1.

In the opinion of this reviewer, the key to understanding the statistical results of the Israeli experiments is contained in the a priori design document for the Israel-2 experiment. It provides the basis for interpreting the various results of the Israel-2 experiment as well as the basis for determining which, if any, results can be considered to be a replication of the Israel-1 results. Rosenfeld (1997) referred to the a priori design document in his rebuttal to Rangno and Hobbs (1995). The document is in Hebrew but a certified English translation was provided to the editor of the *Journal of Applied Meteorology* and subsequently obtained by this reviewer.

According to the a priori design document for the Israel-2 experiment, the experiment consisted of a north area that was to be seeded randomly, a south area that was to be seeded randomly in a crossover manner with the north area, a buffer zone between the north and south areas, and a control area upwind of the north area. Two hypotheses were put forward for testing: 1) seeding would enhance precipitation in the north area when evaluated as a single-area target-control experiment, and 2) seeding would enhance precipitation in the combined north and south areas when evaluated as a crossover experiment. Although the design emphasized the north area because it included the Lake Kinneret catchment area that was important to the water resources of Israel, and expressed some reservations about the benefit of seeding in the south area, both hypotheses were specified in the final design. This leads to the following important implications:

- The Israel-2 crossover experiment can be considered to be a replication of Israel-1. In doing so it must be recognized that the replication was not exact since the boundary areas of the alternating targets changed, a control area was added and aircraft seeding was supplemented by ground-based silver iodide generators. Nevertheless, the Israel-2 experiment was based on the same concept of increasing precipitation by silver iodide seeding at cloud base and, in that sense, it replicated the Israel-1 experiment.
- The North area single-area target-control experiment can be considered to be confirmatory to the extent that it can potentially confirm the a priori design hypothesis of Israel-2.
- The 0.05 level of significance for the Israel-2 experiment should be shared among the two a priori design hypotheses with a value of 0.025 assigned to each.

TABLE 1. Summary of the main statistical results of the Israeli static-mode seeding experiments on rainfall for the indicated targets. One-sided *P* values are given in parentheses after each test statistic value. The designations for the test statistics are defined in the text. Shown in boldface are the a priori evaluation results that are statistically significant when compared to the level of significance obtained by application of the Bonferroni method (0.05/number of a priori evaluations)

	A priori evaluations	**Exploratory analyses**
Israel-1	**RDR = 1.15 (0.009)**	SR (north) = 1.15 (0.16) SR (center) = 1.16 (0.16)
Israel-2	DR (North) = 1.13 (0.028) RDR = 0.98 (0.32)	SR (north) = 1.15 (0.125) SR (south) = 0.83 (0.075)
Israel-3	DR (South) = 0.955 (0.21)	

Based on these criteria and previous but still relevant criteria, the statistical results of the three Israeli experiments, evaluated in accordance with their a priori designs, can be summarized as follows:

1) The Israel-1 crossover seeding experiment resulted in a rain increase of 15% for the combined targets that is statistically significant at the 0.05 level.
2) The statistically significant result of the Israel-1 crossover seeding experiment was

not replicated in the Israel-2 crossover seeding experiment.

3) The Israel-2 single-area target-control seeding experiment for the north area resulted in a 13% increase in rain that is not statistically significant at the 0.025 level.
4) The Israel-3 seeding experiment did not result in a statistically significant change in rain in the south area.

2) Physical evidence

Satellite and in situ cloud physics aircraft measurements indicate that there is large variability in the microstructure of clouds over Israel. Levin et al. (1996) and Rosenfeld and Lensky (1998) found evidence for the occurrence of condensation–coalescence and ice crystal multiplication processes in some clouds, conditions that are not consistent with the physical criteria for applying the static-mode seeding concept. Other clouds were found to have relatively long-lived episodes of supercooled water with little evidence of condensation–coalescence processes (Lahav et al. 1998 and Rosenfeld and Lensky 1998), conditions that are consistent with the physical criteria for applying the static-mode seeding concept. The variability in the microstructure of Israeli clouds is further complicated by incursions of desert dust primarily in the south and to a lesser degree in the north that, according to the desert-dust hypothesis (Rosenfeld and Farbstein 1992), renders clouds affected by the desert-dust nuclei unsuitable for static-mode silver iodide seeding. Thus, the postulated conditions for static-mode seeding that formed the physical basis of the Israeli experiments were not valid for a fraction of the clouds that were treated in the Israeli experiments; how large a fraction cannot be determined since there were no physical measurements accompanying the seeding operations. Rosenfeld (1997), Woodley (1997), and Dennis and Orville (1997) speculated about alternative physical hypotheses to explain the positive results of seeding in the north target that were suggested by the statistical analyses of the Israeli-1 and Israeli-2 experiments; however, given that there were no concomitant physical measurements, there is no way to assess their physical plausibility.

b. Dynamic-mode seeding

1) Statistical evidence

For ease of reference, the statistical results of the various dynamic-mode seeding experiments discussed in section 4 are summarized in Table 2.

The Caribbean experiment focused on individual tropical cumuli and succeeded in demonstrating with strong statistical significance that silver iodide seeding increased their vertical growth under specifiable conditions and that the EMB 65 cloud model predicted with remarkable skill the amount of growth and the conditions required for it. Both the SF68 and SF70 experiments also focused on single convective clouds but extended their consideration of the effects of dynamic-mode seeding to increasing precipitation as well as increasing the cloud's vertical growth, thereby reducing the level of significance for each null hypothesis to 0.025. Both experiments successfully replicated the results of the Caribbean experiment with respect to the seeding-induced increase in the vertical growth of the clouds but neither attained the P value required to gain statistical significance for the observed effect of seeding on rainfall even when the nonrandomly selected radar controls were included in the unseeded samples. Strictly speaking, the SR (R_{40}) rainfall result for SF70 should not be listed among the a priori evaluations in Table 2 because it includes the nonrandomly selected radar controls in its unseeded cloud sample.

Sufficiently encouraged by the rainfall results of the SF68 and SF70 experiments, the FACE-1 experiment was launched in order to test dynamic seeding concepts for rain enhancement in a multiple cloud seeding experiment over a fixed target area in south Florida. Because of the many important changes in the design during the course of the experiment and the multiplicity of analyses thereafter, FACE-1 was considered to be an exploratory experiment (Woodley et al. 1982b) and all the results are, therefore, the product of exploratory analyses. The nature of the results and their consistency among the various analyses, prompted the conduct of the FACE-2 experiment that was designed to confirm the suggestions of seeding-induced rain increases in FACE-1 and to replicate the main analyses of FACE-1. The result was that FACE-2 failed to confirm the findings of FACE-1 and also failed to replicate the main analyses of FACE-1.

Gagin et al. (1986) conducted an exploratory study of the properties of convective rain cells of some of the FACE-2 treated clouds on some B days. To do this they used the method of Rosenfeld (1987) to define and track convective rain cells through their lifetime—that is, until split or merger occurred (called short tracking). They derived data on the height, precipitation intensity and area, duration and total rain volume of the convective rain cells, which they used to esti-

TABLE 2. Summary of the main statistical results of the dynamic-mode seeding experiments on the cloud height (H) and rainfall (R) for the indicated targets. One-sided P values are given in parentheses after each test statistic value. The designations for the test statistics are defined in the text. Shown in boldface are the a priori evaluation results that are statistically significant when compared to the level of significance obtained by application of the Bonferroni method (0.05/number for a priori evaluations)

	A priori evaluations	**Exploratory analyses**
Caribbean single cloud	**$H_S - H_{NS}$ = 1.6 km (< 0.01)**	
SF68 single cloud	**$H_S - H_{NS}$ = 3.5 km (0.005)** SR(R_{40}) = 2.16(0.10), w/o radar controls	SR (R_{40}) = 2.44(0.05), with radar controls
SF70 single cloud	**$H_S - H_{NS}$ = 1.9 km (0.01)** SR (R_{40}) = 1.57 (0.10), with radar controls	SR (R_{LT}) = 2.80(0.05), with radar controls
FACE-1 area		FT (B days) SR (R_{360}) = 1.49 (0.01) TT (B days) SR (R_{360}) = 1.23 (0.08) FT (A+B days) SR (R_{360}) = 1.46(0.03) TT (A+B days) SR (R_{360}) = 1.29(0.05)
FACE-2 area	FT (B days) SR (R_{360}) = 1.08 (0.42) TT (B days) SR (R_{360}) = 1.04 (0.45) FT (A+B days) SR (R_{360}) = 1.2 (0.30) TT (A+B days) SR (R_{360}) = 1.03 (0.45)	
Texas mesoscale cluster	SR (H_{STC}) = 1.00 (0.47) SR (R_{STC}) = 1.69 (0.04) SR (R_{150}) = 1.45 (0.16)	SR (H_{LTC}) = 1.10 (0.21) SR (R_{LTC}) = 2.63 (0.014)
Cuba-1 single cloud	SR (T68) = 1.24 (0.07) SR (R68) = 2.22 (0.07) SR (H68) = 1.08 (0.49) SR (AI68) = 1.64 (0.10) SR (Z68) = 1.05 (0.23) SR (AM68) = 1.38 (0.20)	SR (T) = 1.11 (0.21) SR (R) = 1.47 (0.22) SR (H) = 1.04 (0.77) SR (AI) = 1.31 (0.18) SR (Z) = 1.03 (not given) SR (AM) = 1.20 (not given)
Cuba-2 mesoscale cluster	SR (T68) = 1.21 (0.04) SR (R68) = 1.65 (0.02) SR (H68) = 1.17 (0.01) SR (AI68) = 1.33 (0.03) SR (Z68) = 1.01 (0.84) SR (AM68) = 1.28 (0.05)	SR (T) = 1.15 (0.13) SR (R) = 1.43 (0.04) SR (H) = 1.08 (0.06) SR (AI) = 1.19 (0.07) SR (Z) = 1.00 (not given) SR (AM) = 1.07 (not given)
Thailand mesoscale cluster	SR (R_{LTC}) = 1.35 (0.11) SR (R_{300}) = 1.48 (0.11)	SR (R_{300}) = 1.58 (0.05) SR (R_{600}) = 1.91 (0.03) SR (R_{LTC}) = 1.36 (0.07) SR (H_{LTC}) = 1.03 (0.28)

mate the effect of seeding, if any, on these properties. In particular, they attempted to verify the increases in the depth of the convective cells, which they said was the basic tenet of cloud seeding aimed at producing dynamic effects, and the corresponding increases in the other convective rain cell properties. Gagin et al. (1986) suggested that seeding convective cells for dynamic effects increased their total rainfall by positively affecting their other properties, and that the positive changes in their properties could be predicted from the changes in maximum cell height following seeding. The effect of seeding appeared to be greatest for cells that were treated early in their life cycle with 600 g of silver iodide or more.

The Texas experiment was designed, conducted, and analyzed in accordance with the dynamic-mode seeding conceptual model that guided the FACE experiments. In view of this and the stated importance that seeding effects would first be manifest on the scale of convective cells as shown by the FACE-2 exploratory analyses of Gagin et al. (1986), at least three null hypotheses were implicit in the design: 1) seeding does not increase the maximum height of treated short-track convective cells, 2) seeding does not increase the precipitation from treated short-track convective cells, and 3) seeding does not increase the precipitation from treated experimental units. Thus, the level of significance for each of the null hypotheses is 0.0167. The concept of long-track cells was first introduced during the analysis of the Texas data so the evaluation of the long-track cells must be considered as exploratory and its results must be viewed with caution because the cell long-tracking procedure occasionally produced cells with duplicate histories in the latter portion of their life. The evaluation of the Texas experimental data (Rosenfeld and Woodley 1993; Woodley and Rosenfeld 1996), indicated that none of three null hypotheses could be rejected at the appropriate level of significance. The findings of the exploratory analyses of short-track cells by Gagin et al. (1986) were not replicated by the Texas experiment.

The Cuba experiments were also designed, conducted, and analyzed in accordance with the dynamic-mode seeding conceptual model that guided the south Florida and FACE experiments. An assessment of seeding effects was made for six radar-estimated properties of the individual convective clouds (Cuba-1) and the mesoscale cloud clusters (Cuba-2). If the subset of clouds that the exploratory experiment indicated as most suitable for seeding, that is, the subset with echo top heights between 6.5–8.0 km at the time of treatment, is interpreted as representing the primary null hypotheses intended by the confirmatory experiment, then the appropriate level of significance for the SR of each of the six radar-estimated properties is 0.0083. On that basis, the SR values for all of the radar-estimated properties for both the individual convective clouds (Cuba-1) and mesoscale cloud clusters (Cuba-2) were not statistically significant.

The evaluation of the Thailand experiment in accordance with its a priori design did not yield statistically significant results. There was no statistically significant change in the radar-estimated rain volume of either the convective cells or experimental units. An examination of the Thailand cold-cloud experimental data given in Woodley et al. (1999c) indicates that the randomization produced a “bad draw” during the experimental unit qualification process such that the rain volume of the seeded experimental units prior to selection was significantly greater than that of their unseeded counterparts. When this potentially compromising covariate is taken into account in the evaluation of the a priori and exploratory data samples, it is likely that the already nonsignificant results will be weakened further.

2) Physical evidence

The dynamic cold-cloud seeding conceptual model evolved over time. At first, it was based on the premise that a seeded cloud would produce similar rain amounts as an unseeded cloud of the same height and that rain amount increases with increasing cloud depth. Thus, it was postulated that massive seeding of the supercooled portion of the cloud would freeze the water, that the resulting release of latent heat would increase the buoyancy of the seeded volume making the cloud grow taller, and that the seeded cloud would produce more rain than its unseeded counterpart as a result of its increased depth. The Caribbean and south Florida experiments appeared to confirm that seeding caused the clouds to grow taller but they did not provide the required statistical evidence that it resulted in the production of more rain.

At the end of the FACE-1 experiment, a detailed statement of the dynamic cold-cloud seeding conceptual model was formulated (Woodley et al. 1982b); referred to here as dynamic cold-cloud seeding conceptual model 1. It specified the key links in the chain of physical events from the seeding of the initial cloud towers to an increase in area rainfall. It elaborated on but did not alter the basic premises of dynamic cold-cloud seeding underlying the earlier experiments. The seeding was hypothesized to produce rapid glaciation of the supercooled cloud liquid water content (SLWC) in the updraft, the release of latent heat that would invigorate the updraft and increase the vertical growth of the seeded towers. Pressure falls beneath the actively growing towers due to acceleration and upper-level warming would then be followed by increased inflow at mid- and low levels, thereby fueling the initial stage of cloud growth. These processes would result ultimately in increased precipitation and enhanced downdrafts (Simpson 1980) from the seeded clouds.

The enhanced convergence at the interface between the downdraft outflows and the ambient flow acts to stimulate more neighboring cloud growth, some of which will also produce precipitation. When seeding is applied to towers within several neighboring cells, increased cell merging and growth will result. The enhanced convergence and cell mergers lead to an expansion of the cloud system and its conversion to a fully developed cumulonimbus system. The net effect is increased rainfall over the target area.

From the outset, the dynamic cold-cloud seeding conceptual model 1 was challenged. Three-dimensional time-dependent model simulations were not able to show that the effects of latent heat release in midlevel were transmitted to lower levels via pressure changes (a key link in the postulated chain of physical events), which would then modify the circulation of the cloud substantially (Levy and Cotton 1984). Then, contrary to the postulates of dynamic cold-cloud seeding conceptual model 1, the results of the Texas experiments suggested that seeding did not increase the height of the convective cells and that the seeded clouds produced more rainfall than unseeded clouds of the same height. This caused a rethinking and modification of dynamic cold-cloud seeding conceptual model 1 and the creation of dynamic cold-cloud seeding conceptual model 2 (Rosenfeld and Woodley 1993).

According to dynamic cold-cloud seeding conceptual model 2, the seeding is hypothesized to produce rapid glaciation of SLWC in the updraft by freezing preferentially the largest drops so they can rime the rest of the cloud water into graupel. This seeding-induced graupel is postulated to grow much faster than raindrops of the same mass so that a larger fraction of the cloud water is converted into precipitation before being lost to other processes. Ice multiplication is not viewed as a significant factor until after most of the cloud water has been converted into precipitation. This faster conversion of cloud water into ice precipitation enhances the release of latent heat, increases cloud buoyancy, and invigorates the updraft that acts to support the growing ice hydrometeors produced by the seeding and, although not necessarily, to spur additional cloud growth. Thus, the basic tenet of dynamic-mode seeding under seeding conceptual model 1 was discarded—that is, that seeding convective cells increased their total rainfall as a result of increasing their depth (Gagin et al. 1986). Instead, it was postulated in seeding conceptual model 2 that the retention of the precipitation mass in the cloud's upper portions caused by the seeding-induced invigoration of the updraft delays the formation of the precipitation-induced downdraft. This delay allows more time for the updraft to feed additional moisture into the growing cloud, thereby fueling additional growth of the hydrometeors. These processes result ultimately in increased precipitation and enhanced downdrafts from the seeded clouds, leading to enhanced convergence, enhanced cell mergers, the conversion of the cloud system into a fully developed cumulonimbus system, and a net increase in rainfall over the target area as indicated in dynamic cold-cloud seeding conceptual model 1.

Dynamic cold-cloud seeding conceptual model 2 was put to the test in the Thailand experiment. Thus, it can be considered as an attempt to replicate and extend the exploratory results of the Texas experiment and confirm the revised conceptual model that grew out of the Texas exploratory analyses. A statistically significant change in the radar-estimated rain volume was, however, not indicated for either the convective cells or experimental units. Contrary to the postulates of dynamic cold-cloud seeding conceptual model 2, it was found that the directly treated clouds did not exhibit the prescribed effects of seeding; there was no statistically significant increase in rainfall, and the rainfall and presumably the enhanced downdraft produced by it did not appear to be delayed (Woodley et al. 1999c). Another apparent inconsistency with the seeding conceptual model, evident in the results of Woodley et al. (1999c), was the strong suggestion that the average maximum radar reflectivity for the seeded units was less than that for the nonseeded units, a result that seems to be in conflict with the strong suggestion that the average maximum radar reflectivity for the seeded cells was greater than that for the nonseeded cells. The exploratory analysis by Woodley et al. (1999c) also showed that the difference in average rain volume between the S and NS cases did not manifest itself until about 2 h after unit qualification or shortly after the average time of seeding termination. The difference in average S and NS rain volume increased steadily with time thereafter until it reached a maximum at about 8 h after experimental unit qualification or about 6 h after the average seeding termination time. If it is assumed that seeding was indeed responsible for the above-suggested effects, yet another revision of the dynamic cold-cloud seeding conceptual model will be required to account for them.

The replacement of seeding conceptual model 1 by seeding conceptual model 2 was triggered by the finding in the Texas experiment that seeding did not increase the height of the convective cells and the suggestion that the seeded clouds produced more rainfall than unseeded clouds of the same height. A similar finding was suggested by the results of the Thailand experiment. Based on an examination of the effect of seeding on radar-estimated cloud-top height for a subset of Texas and Thailand clouds that were deemed to be most suitable for glaciogenic seeding intervention according to seeding conceptual model 2, Woodley and Rosenfeld (2000) concluded that the link in seeding conceptual model 1 calling for increased growth of the clouds following seeding should be retained in seeding conceptual model 2 as a likely, but not a necessary, manifestation of the seeding-induced invigoration of the updraft. They pointed out that cloud-top height in the Caribbean and Florida single cloud experiments, which showed that seeding produced statistically significant increases in cloud-top height, was measured visually by an aircraft flying above the cloud top. In Texas and Thailand, on the other hand, estimates of cloud-top height were made using a 5-cm and 10-cm radar, respectively, at a reflectivity threshold of 12 dBZ. Therefore, the visual cloud tops in Texas and Thailand were underestimated with respect to those in the Caribbean and Florida. More to the point, they inferred that the cloud-top height of seeded clouds in Texas and Thailand were underestimated more than their unseeded counterparts because the seeding is postulated to change the microphysical structure of the clouds in such a way as to cause the reflectivity of those clouds to fall off faster with height above the freezing level. Thus, the difference in the actual physical height between seeded and unseeded clouds may be greater than the difference in radar-estimated heights and that difference may even be statistically significant. It is important to resolve this uncertainty because it will help explain a major inconsistency in the results of the various dynamic-mode seeding experiments, that is, the diverse effects of seeding on cloud-top height. It could also provide the most credible evidence to date that seeding actually invigorated the updraft, a pivotal link in the chain of physical events postulated by the seeding conceptual model.

6. Conclusions

Based on a rigorous examination of the accumulated results of the numerous experimental tests of the static-mode and dynamic-mode seeding concepts conducted over the past four decades, it has been found that they have not yet provided either the statistical or physical evidence required to establish their scientific validity. Thus, the conclusion of several high-level reviews of weather modification conducted by the Advisory Committee on Weather Control, the National Academy of Sciences, and the Weather Modification Advisory Board during the period from 1957 to 1978 that cloud seeding was promising, unproven, and worth pursuing is still valid today.

A rigorous interpretation of the statistical evidence for the Israeli experiments leads to a finding that seeding had no effect on either the north or south (or center) target and the appropriate hypothesis is N_0S_0. The Israel-1 crossover seeding experiment resulted in a rain increase of 15% for the combined targets that is statistically significant at the 0.05 level, but that result was undermined when it was not replicated in the Israel-2 crossover seeding experiment. Some of the exploratory analyses have suggested that the appropriate hypothesis might be N_+S_0, that there was a positive effect of seeding in the north and no effect in the south. Perhaps the strongest support for a possible seeding effect in the north is the finding that, as predicted, the area indicating a maximum in the S/NS ratio in Israel-1 shifted eastward in Israel-2 when the seeding line was shifted eastward a commensurate distance. These arguments notwithstanding, any suggestion of a positive statistical result of seeding in the north must be viewed with caution. 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, and the applicability of the static-mode seeding conceptual model to Israeli clouds has been seriously undermined. It has been shown that some, not yet quantified, fraction of the convective clouds in Israel produce large cloud droplets, precipitation-sized drops, high concentrations of ice crystals, and precipitation at relatively warm cloud-top temperatures, and/or are contaminated by desert-dust nuclei, all of which are not consistent with the physical criteria for applying the static-mode seeding concept.

According to the proof-of-concept criteria, numerous investigations of the dynamic-mode seeding concept over the past 35 years have failed to provide either the statistical or physical evidence required to establish its credibility. None of the experiments resulted in a statistically significant increase in rainfall in accordance with its a priori design. The physical evidence consists of small samples of physical measurements taken under conditions of high cloud-to-cloud variability, and many of these physical measurements were not taken in the clouds that were randomly selected for treatment during the experiments. The most that could be concluded from these supporting physical studies was that their results were consistent or, more precisely, not inconsistent with the dynamic cold-cloud seeding conceptual model as postulated at that time. The first version of the dynamic cold-cloud conceptual model postulated a seeding-induced increase in maximum cloud-top height and, indeed, it appeared to occur in the Caribbean and south Florida experiments. The results of the Texas experiment prompted a significant revision to the dynamic cold-cloud seeding conceptual model whereby a seeding-induced increase in the invigoration of the updraft, but not necessarily an increase in the maximum cloud-top height, was postulated; however, the postulated invigoration of the updraft has never been verified. Each of the dynamic-mode seeding experiments was based on a stated seeding conceptual model with explicit hypotheses, the testing of which resulted in evaluations based on the a priori design that failed to reach statistical significance and numerous exploratory analyses that purported to show positive seeding effects. In the opinion of this reviewer, the reports of the results of these experiments placed greater (exaggerated) emphasis and meaning on the suggestive but iffy rainfall results of the exploratory analyses, which have never been confirmed or replicated in subsequent experiments, than on the disappointing but valid evaluations in accordance with their a priori designs.

In summary, the research and experiments related to the static-mode and dynamics-mode seeding concepts, especially those conducted since 1978, provided physical insights about some important cold-cloud precipitation development mechanisms and the possible effect of glaciogenic seeding on them. 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. New experiments are needed to resolve the uncertainties, inconsistencies, and deficiencies in the statistical and physical evidence in support of static-mode and dynamic-mode seeding of convective clouds obtained thus far. Considering the statistically positive results of hygroscopic flare seeding of cold convective clouds in South Africa (Mather et al. 1997 and Silverman 2000), its replication in Mexico (Bruintjes et al. 1998), and of hygroscopic particle seeding of warm convective clouds in Thailand (Silverman and Sukarnjanaset 2000), efforts to obtain the physical evidence required to place the hygroscopic seeding concept on a secure scientific foundation is, perhaps, a more immediate and higher-priority investment. This conclusion is supported by the results of the numerical model experiments by Reisen et al. (1996), which suggest that hygroscopic particle seeding could be much more productive than glaciogenic seeding in enhancing rainfall from cold convective clouds, and could be easier to apply because the optimal time window for seeding is longer.

The statistically positive hygroscopic seeding experiments carried out in South Africa, Thailand, and Mexico were single-cloud experiments that postulated an increase in precipitation would be produced by microphysical effects induced by the seeding, that the seeded clouds would be transformed into more maritime clouds making them more efficient precipitators. However, it was necessary in all three experiments to invoke the occurrence of seeding-induced dynamic effects to explain the results. 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 WMO convened a workshop on hygroscopic seeding (WMO 2000) to review the statistically significant 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 were responsible for the statistical results and, based on that understanding, to design a physical–statistical experiment to demonstrate that rain increases could be achieved on an areawide basis. High priority should be given to the implementation of this program plan lest we be condemned to repeat past mistakes in the development and application of glaciogenic seeding as we move forward with the development and application of hygroscopic seeding. In general, a better understanding of how the timing, location, and intensity of downdrafts affects the autopropagation of a convective cloud system is needed to assess the potential of both the hygroscopic and glaciogenic seeding concepts.

Future research on glaciogenic seeding of convective clouds, indeed any cloud seeding technique, should feature well-defined physical–statistical tests of the seeding concepts, in accordance with the proof-of-concept criteria, in order to establish their scientific credibility. Credibility cannot be achieved through further exploratory analyses of the existing experimental data no matter how promising and consistent the results may seem. The new tests should be preceded by physical measurements in order to develop relevant and testable physical hypotheses for the clouds in the selected experimental area, as was done in the WMO PEP experiment. The development and evaluation of these physical hypotheses should be strongly supported by the use of suitable numerical cloud models covering all scales of interaction that are expected, an important tool that seems to have played only a minor role in the conduct of past experiments. The physical hypotheses should be the basis for formulating well-defined statistical hypotheses and an efficient experimental design to test them. If the results of these design efforts indicate that statistical tests are warranted and feasible, the tests should be accompanied by physical measurements designed to verify the physical plausibility of the statistical results by confirming the key links in the postulated chain of physical events. The physical evidence is needed to verify the cause-and-effect relationship between seeding and the statistical result on all relevant scales of motion. It is needed to establish the physical basis for applying the technology on an areawide basis, for transferring the technology to other geographical areas, and for implementing operational seeding projects.

Finally, people with water interests at stake who are investing in operational glaciogenic cloud seeding projects for precipitation enhancement should be aware of the inherent risks of applying an unproven cloud seeding technology and provide a means of evaluation that allows for an assessment of the scientific integrity and cost effectiveness of the operational seeding projects. Those who are contemplating investing in operational hygroscopic seeding projects for precipitation enhancement based on the statistically positive experimental results in South Africa, Thailand, and Mexico should be aware that, in the absence of physical evidence required by the proof-of-concept criteria, this cloud seeding technology is also unproven.

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