

Assessing the Potential for Rain Augmentation—The Nelspruit Randomized Convective Cloud Seeding Experiment

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ABSTRACT

The experimental design, analyses, and results of the first Nelspruit randomized cloud seeding experiment are described. The experiment ran for three years, commencing in October 1984, and involved the on-top seeding of new cloud turrets growing on the flanks of isolated multicellular storms using dry ice delivered from a Learjet at around the height of the -10°C isotherm. All storms were tracked by a radar operating in computer-controlled volume scan mode. A total of 169 storms were examined, of which 94 passed the selection criteria. The most important criterion was based upon a microphysical classification scheme obtained from measurements made by the instrumented Learjet. This scheme, based upon a ratio of cloud-base temperature to potential buoyancy at 500 mb, rejected those storms in which the production of precipitation via coalescence was unlikely.

A key element of the experiment was the ability to objectively track the storms using an automatic storm tracking algorithm. Storms were analyzed in terms of their track properties, some of the more important of which were storm volume, area, and rain flux. Analyses of these track properties in 10-min time intervals either side of decision time (the time the seed/no-seed decision was made) proved to be the most revealing in terms of observed changes and rates of changes in convective cloud processes. This analysis showed an almost fourfold percentage increase in radar-measured rain flux and storm area when the seeded and control storms were compared.

A confirmatory experiment was conducted in the third season. Storm track properties that showed an apparent response to seeding in each of the first two seasons were selected prior the commencement of the third season. All but one of these track properties either stayed the same or showed increases in the third season, confirming the hypothesis that there were radar-detected differences between the seeded and control storms.

1. Introduction

This paper describes the experimental design, the analyses, and the results of the Nelspruit randomized convective cloud seeding experiment. It is the first comprehensive description of this completed experiment.

The experimental area centered around Nelspruit, South Africa, where the project radar was located. Nelspruit lies at $25^{\circ}30'S$, $30^{\circ}55'E$ at an altitude of 980 m above sea level. The area is bounded on the west and south by high terrain (about 1800 m), which is broken in many places by deep river valleys. To the east, the land gradually tapers off to the Mozambique border,

where it becomes relatively flat. Most of the convection that supplies over 90% of the annual rainfall is initiated over the high terrain.

Studies of the behavior of storms over this complex terrain have been conducted in phase 1 of the Nelspruit program and can be found in reports published by the Water Research Commission (1986). These studies showed that, while echo frequencies and direction of storm movements are related to terrain features, radar-measured storm characteristics such as cloud-top heights and storm sizes are not.

The design of the experiment was aided by results from two major American experiments, the Florida Area Cumulus Experiment (FACE I and II) and the High Plains Cooperative Program (HIPLEX-I). The FACE experiments were based on the dynamic cloud seeding concept, the theory that massive artificial ice nucleation in updraft regions increases buoyancy

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through release of the heats of fusion, deposition, and condensation, thereby producing taller, wider, and longer-lasting clouds (Simpson et al. 1965). This conceptual model evolved during the years of the experiment to include increases in cloud growth leading to mesoscale organization through cloud mergers and downdraft invigoration (Simpson 1980).

Facets of the FACE I experiment that influenced the design of the Nelspruit experiment were the use of a floating target to provide a more sensitive measure of the effects of seeding (it is a small step conceptually from a floating radar target to an objective storm tracking scheme) and the finding that radar-estimated rain measurements were accurate enough to make inferences regarding a seeding effect (Woodley et al. 1982). It was concluded through the work in Florida that there is no difference between the Z - R relationship in seeded and control clouds, where Z is equivalent radar reflectivity and R is rain rate. Yet more important was the observation that even if there were differences, they were small compared to the between-day variability (Cunning 1976). This also implies that the choice of a particular Z - R relationship is not of critical importance. Attempts to use rain gauges to adjust radar estimates of rainfall in the FACE II experiment were not entirely successful. While mean agreement was improved, the day-to-day variation of differences was not diminished. This was attributed to spatial variation of gauge-to-radar rainfall ratios within the target area. This implies variations in R versus Z between storms within the target area (Barnston and Thomas 1983). Work by Wilson and Pollock (1974) (who used the Marshall-Palmer Z - R relationship) showed that the accuracy of the radar measurements was relatively insensitive to the Z - R relationship used. This study and advice from program consultants led to the choice of the $Z = 200R^{1.6}$ relationship, the value that was in use prior to the commencement of the experiment.

The HIPLEX-I experiment chose dry ice as the seeding agent because of the consistency of cloud response to dry-ice seeding. The advantages of using dry ice rather than silver iodide are listed in Holroyd et al. (1978). Effectiveness was estimated to be between 10^{12} and 10^{13} ice crystals per gram of dry ice (Cooper et al. 1982).

The statistical analyses of the HIPLEX-I results indicated strong responses from 3 of the 23 primary, secondary, and final test statistics. These strong responses occurred in the first 5 min after seeding and were a result of pronounced differences in the development of ice crystals in the seeded and unseeded clouds. Response variables measured more than 5 min after treatment generally did not show significant differences between seeded and control clouds (Mielke et al. 1984). This was attributed to the rapid decay of liquid water content in HIPLEX-I clouds. Perhaps the most important result to emerge from the HIPLEX-I experience was the recommendation to move to convective com-

plexes as the best candidates for continued experimentation.

The results from the Canadian silver iodide experiments at Thunder Bay and Yellowknife also emphasized the importance of cloud lifetimes. Clouds of short duration did not provide adequate time for the seeding-induced ice crystals to grow to precipitation sizes. This work suggested that the rain forming process might be sped up by the use of dry ice as the seeding agent, thus eliminating any possible nucleation lags (Isaac et al. 1982).

Experiments similar to HIPLEX-I were conducted at Bethlehem in the Orange Free State, South Africa, during the summer of 1984-85. A three-way randomization scheme using dry-ice pellets, silver iodide flares, or a placebo was adopted. The experimental units were semi-isolated cumulus congestus clouds. The results conclusively demonstrated that some cumulus clouds were modified by the ingestion of either silver iodide or dry ice. Dry ice appeared to be the superior ice nucleating agent. Fewer ice seeding signatures were detected in clouds seeded with silver iodide (Krauss et al. 1987). As in the Canadian experiment, the time lag in silver iodide activation was advanced as the probable reason. Again, cloud lifetimes were found to be the principal factor limiting precipitation development in treated clouds. A recommendation to move upscale to convective complexes was made here as well.

In summary, the FACE I experiment showed evidence of apparent dynamic seeding effects, but only 2 h after the commencement of seeding. FACE II failed to confirm this result. HIPLEX-I and the Bethlehem experiments both showed static seeding responses not leading to increased rainfall. There was some evidence in the Bethlehem experiment of a dynamic reaction from dry ice.

At Nelspruit, trials had shown convincing evidence of the superiority of dry ice over silver iodide as an ice nucleating agent (Garstang et al. 1981). The dilemma faced at Nelspruit was the difficulty of separating microphysical from dynamical seeding responses in convective complexes. These circumstances made formulation of a seeding hypothesis prior to the commencement of the experiment difficult. At that time, numerical models were of little help.

Considering the results of these experiments, the hypothesis of the Nelspruit experiment simply stated that there would be radar-detectable differences between seeded and unseeded storms. The first two years of the experiment were exploratory. During this phase, probability p values were used as a measure of the strength of the apparent seeding effects and strictly speaking were not a measure of statistical significance since the anticipated differences between the seeded and no-seed storms were not specified prior to the commencement of the experiment. The final year was at least partially confirmatory. The physical insights gathered during the

experiment have led to the postulation of a seeding hypothesis.

2. Equipment

a. The radar

A Pacer III radar (manufactured by Sierra Research Corporation) was used for the seeding experiment. Its characteristics are

- frequency, 5.61 GHz (C band);
- peak power, 250 kW;
- pulse duration, 2.3 μ s;
- pulse repetition frequency, 197.5 s⁻¹;
- beam width, azimuth 1.85°;
- elevation, 1.50°; and
- gain, 38.4 dB.

An L-band transceiver mounted on the radar dish is used to interrogate standard aircraft transponders. The return signal is displayed on the radar screen along with the radar returns from storms, permitting the radar operator to direct the project aircraft to storms of interest.

The location of the radar at Nelspruit, in a valley surrounded by hills on three sides, was not ideal for radar measurements of rainfall. The lowest practical elevation angle of the radar scan sequence was 3°. The scan-angle sequence that was used sampled the same volume at 3° elevation at a range of 120 km as at 50° and 15 km.

b. Radar range limitations

Since precipitation normally decreases with height, the tilt of the radar beam results in apparent decreases in reflectivities as the range from the radar increases. This is exacerbated by the well-known beam-filling problem (Atlas et al. 1990). These effects were evaluated for the Nelspruit radar, putting a limit upon the useful range of the radar. A season (1984–85) of volume scan radar data was examined for such effects. The mean positions of all storm tracks were stratified into 20-km annuli, as shown in Table 1. The vertical scan limits had a lower bound of 3° from the radar (4.2 km at 80 km) and an upper bound of 16 km MSL. The mean storm positions are weighted by the storm volume for each scan as follows. Mean x (y) is the sum of the products of the x (y) centroid and storm volume

for each scan, divided by the sum of the volumes for each scan. The mean storm position is the hypotenuse of the mean x and y . The areas were normalized by dividing each area by the area of the first annulus and the tracks by the number of tracks recorded in the first annulus. The number of normalized tracks should roughly correspond to the normalized area. This is true up to about annulus 7, after which the number of tracks begins to lag behind the normalized area. This suggested a sampling problem beyond this range. Evaluation of average measurements of storm areas, reflectivity factors, and rain fluxes indicated degradation in the measurements of rain fluxes beyond about 80 km from the radar, caused mainly by rapid increases in average storm areas. This can be ascribed to the radar beam-filling problem. As a result of these tests, useful data were considered to be restricted to the range of between 10 and 80 km from the radar.

c. The radar computer

The radar scan was controlled via keyboard commands to a computer that also digitized and formatted the radar reflectivities and returns from aircraft transponders for recording on magnetic tape and display on a color monitor. Only the lowest scan was displayed and held while the radar stepped through the rest of its scan sequence.

d. The research computer and software

Software written in-house applied the radar equation and the range correction, and eliminated the areas of each scan that were free of radar echoes. These data, including aircraft position, were then archived. In addition, 63 storm properties, listed in appendix A, were also computed.

Crucial to the experimental design was the capability to objectively track storms that would be chosen for seeding trials. A modified version of a storm tracking algorithm from Mader (1979) was developed for this purpose.

Once storm tracks had been identified, up to a total of 244 storm track properties were computed. Statistical rerandomization routines were developed to test the significance of differences in track properties between storm classes.

TABLE 1. Data that were used to place a limit upon the useful range of the radar for the seeding experiment.

Annulus number	1	2	3	4	5	6	7	8	9	10	11
Inner range (km)	0	10	20	30	40	50	60	70	80	90	100
Outer range (km)	20	30	40	50	60	70	80	90	100	110	120
Mean (km)	10	20	30	40	50	60	70	80	90	100	110
Number of storm tracks	155	359	578	868	1058	1087	1002	801	578	427	307
Normalized area	1	2	3	4	5	6	7	8	9	10	11
Normalized tracks	1	2.3	3.7	5.6	6.8	7.0	6.5	5.2	3.7	2.8	2.0

e. The aircraft computer

A computer was installed in the Learjet. Software was developed to calculate and display time histories of temperature, vertical gust velocities, cloud liquid water contents, and particle concentrations encountered in cloud penetrations on two graphics display units—one for the pilots and the second for the scientific observer. Software was also developed for the research computer to analyze, display, and archive the cloud physics measurements collected by the aircraft.

f. The aircraft

The project's Learjet was used for both sampling cloud properties and cloud seeding. The rapid rates of climb, upper-air maneuverability, dash speed, excellent performance in heavy icing, and structural strength of this aircraft make it an ideal vehicle for this dual role.

Standard measurements of altitude, airspeed, and temperature were recorded, as were measurements of dewpoint (by a Peltier cooled mirror system, EG&G model 13703). Two Particle Measuring Systems (PMS) laser probes were neatly recessed into each wingtip fuel tank—a forward-scattering spectrometer probe (FSSP-100) and a 2D imaging probe (OAP-2D-C).

Updrafts were computed from measurements using a true gust velocity measuring system, consisting of a standard angle of attack vane, a rate gyro, and an accelerometer that measure aircraft pitch rates and vertical accelerations, respectively. Overall accuracy of this system is about $\pm 1 \text{ m s}^{-1}$.

Cloud water was measured in a number of ways.

- A PMS King-CSIRO hot-wire device measured the cloud water contained in droplets smaller than about $100 \mu\text{m}$ in diameter.
- When particle densities could be determined, the PMS 2D-C probe measured the precipitation water content of particles $200\text{--}1200+ \mu\text{m}$ in diameter.
- The jet engine compressors were utilized as evaporators, which converted all cloud condensate into vapor. The vapor density was measured in air extracted from the eighth-stage compressors by a Lyman-alpha humidimeter (Morgan et al. 1989). This yielded a measure of total cloud water content, including vapor, cloud water, and precipitation.

The proportion of the cloud water that has been converted into precipitation (drops larger than $100 \mu\text{m}$ in diameter) at a given level in a cloud provides a measure of the precipitation efficiency of a cloud. When all available cloud water has been converted into precipitation, the cloud is 100% efficient. A measure of this efficiency is the conversion ratio (CR), defined as

$$\text{CR} = 1 - \text{PMS hot-wire} / (\text{Lyman-alpha} - \text{water vapor}).$$

Thus, CR can vary from 0 (no cloud water converted into precipitation) to 1 (all cloud water converted into precipitation).

Measurements of vertical velocities and cloud water contents are extremely important in convective clouds since both are closely linked to the precipitation formation processes. A cloud's rainfall production potential is a function of its cloud water content. Precipitation processes are time dependent; given too vigorous an updraft, the time available for significant precipitation growth becomes too short.

The aircraft radar was used to determine the density of newly formed precipitation embryos, revealing the predominant precipitation formation process that was active in the cloud being sampled. Prior to a penetration at around -10°C , the radar was locked in a level attitude facing forward along the flight path. A single radar range gate was sampled 1800 m ahead of the aircraft. The particle sizes in this volume were sampled 12 s later. Reflectivity factors were computed from

$$Z = \sum n_i D_i^6$$

summed over all particle sizes in the observed volume, where Z is reflectivity ($\text{mm}^6 \text{m}^{-3}$) and n_i is the number of particles (m^{-3}) in discrete intervals of D_i —particle diameter (mm), assuming water drops (density of 1 g cm^{-3}) and graupel of densities 0.8, 0.6, 0.4, and 0.2 g cm^{-3} . These estimated reflectivity factors were compared to the signal recorded from the radar, suitably lagged to bring the two measurements into spatial congruence. The best fit provided an estimate of average particle densities along the sampling path (Mather 1989).

Two bins were installed in the aircraft, each being capable of holding 45 kg of dry ice. The bins were rigged to deliver pellets of dry ice about 1 cm in diameter and 0.2–3 cm long at a rate of about 0.2 kg s^{-1} (1.3 g of dry ice per meter of flight path).

3. Method

a. Introduction

The Nelspruit seeding experiment, which commenced on 1 October 1984, was both a confirmatory and an exploratory experiment: confirmatory to demonstrate the existence of radar-detectable differences between seeded and untreated clouds, and exploratory to discover what these differences were and to find the best way to measure them.

Isolated multicell storms with average volumes of about 170 km^3 were chosen as the experimental units for the following reasons.

- This medium-sized convective complex occurs frequently and produces about 50% of the region's annual rainfall.
- Such convective complexes are large enough to provide a long-lasting source of supercooled water, a feature that was lacking in the clouds chosen for tests

in the HIPLEX (Dennis et al. 1984) and BPRP (Bethlehem Precipitation Research Project) experiments (Kraus et al. 1987). In both of these experiments, by the time the ice crystals produced by the seeding had grown large enough to begin riming, natural entrainment had depleted most of the supercooled cloud water.

- The storm tracking program easily tracks this entity.

Researchers from both experiments recommended that convective complexes should be selected in any follow-on experiments and that the seeding targets should be newly developing cloud turrets growing on upshear flanks.

While the convective complex was the unit chosen for the experiment described here, no attempt was made to track individual cells. The complete storm was tracked on radar, on the premise that seeding the newly developing turrets would affect the storm as a whole. This was based upon the precept embraced at Nelspruit that the new turrets grow to become the main storm. [See Chisholm and Renick (1972) for a detailed description of the multicell storm concept.]

b. Experimental procedure: 1984–85 and 1985–86

A radiosonde was launched each morning at 0800 local time. Calibrations were run and the radar placed in volume scan mode at 0900. A briefing was held at 1030 at which a forecast was issued, based upon the local sounding and upper-air (0000 UTC) and surface (0600 UTC) data received from the South African Weather Bureau. Forecasts were for “go,” “standby,” or “no go” days. The radar was manned on both go and standby days.

The Learjet was launched when two or more clearly separated radar echoes exceeded 40 dBZ. This criterion avoided launches in marginal conditions, since experience had shown that once this condition was met the probability was high that at least one experiment would take place.

The radar operator directed the Learjet to the stronger of the two echoes. The pilots then accepted the storm as an experiment if one or more fresh cloud turrets were growing vigorously through the -10°C level. These new turrets were visually selected for treatment by the crew of the Learjet if,

- the storm had a well-defined base—that is, the cloud tops were not separating from their bases—and
- the growing turrets had reasonable dimensions—that is, good storm width-to-height ratios (0.5 or more)—and were not excessively sheared (less than a 30° tilt).

If the storm satisfied these criteria and was clearly visible on radar and within the range limitations, an experiment was declared and the radar operator immediately opened the first of a paired series of envelopes.

If the instruction was “seed,” the second of the pair of envelopes was destroyed and the storm was seeded (seed/sample).

If the instruction was “no-seed,” then the second of the pair of envelopes was opened. If the instruction in the second envelope was “sample,” a mock seeding took place, which mimicked a seed operation in every detail except for the release of dry ice (no-seed/sample).

If the instruction in the second envelope was “no-sample,” then the storm was marked by flying two orbits close to the area where the seeding would have taken place, but clear of all cloud (no-seed/no-sample).

All seeded clouds were treated between the -5° and -15°C levels by penetrating the target cloud. The instrumentation tape recorder was switched on about 30 s before cloud entry and off 10 s after cloud exit. The seeding button was depressed upon cloud entry and released on cloud exit. This time was recorded and seeding continued until the accumulated seeding time reached approximately 120 s. Postseed passes were permitted between seeding runs and at any level, but the primary emphasis was upon seeding all new cloud growth during the allotted seeding time, with the intention of maximizing any seeding effects. The experimental storms thus selected and treated were tracked throughout their lifetimes by the project radar.

The three-way randomized design was used to investigate whether or not any aircraft-produced ice crystals (APIPS) (Rangno and Hobbs 1983) had an effect upon the clouds that were sampled but not seeded.

At the end of each day the tapes were analyzed by the software described in section 2. The experimental storms were identified by coincidence in space and time of the storm and aircraft tracks. Confusion in track identification led to the rejection of 4 out of a total of 169 storm tracks. An experiment was also rejected if the candidate storm could not be tracked through at least three consecutive volume scans (storm duration of at least 18 min).

As the experiment progressed, it was discovered that on occasion, the tracking program would track a squall line as a single entity. To eliminate these few cases, the storm volume at decision time had to be between 0 and 750 km^3 .

One of the most beneficial by-products of the seeding experiment was increased understanding of the local precipitation formation processes. The Learjet samples a small portion of a storm volume on a single pass. By amassing many such penetrations into a kind of composite storm mosaic, patterns emerge. For example, large drops were often encountered on cloud penetrations at -10°C , indicating the presence of a coalescence or “coalescence-freezing” precipitation formation mechanism (Braham 1986). Attempts to separate those clouds with drops appearing at -10°C from the others, based upon air mass properties, pre- and post-

frontal situations, etc., were not successful. Eventually a simple classification scheme was developed based upon the temperature at the convective condensation level (T_{ccl}) and the temperature difference at 500 mb between the pseudoadiabatic through the T_{ccl} and the environmental temperature (ΔT_{500}). These two quantities were calculated from either the aircraft sounding or the morning Nelspruit sounding (Mather et al. 1986). This result suggests that thermodynamics (local soundings) exert a strong control on the local cloud microphysics and should be included as an integral part of any cloud seeding experiment. A subjectively chosen ratio of T_{ccl} to ΔT_{500} of 2.0 appears to adequately discriminate between those clouds with drops at -10°C from those with either no drops or ice crystals at this level.

This classification was applied to the radar data at the end of the second experimental season. Only those cases whose T_{ccl} to ΔT_{500} ratios were 2.0 or greater were included in the analysis. The value of this ratio was arrived at by a successful partition of the aircraft microphysical data. No efforts were made to "fine tune" the ratio to bring out the maximum statistical response from the radar data. This ratio, termed the coalescence time parameter, is roughly proportional to the time taken for a cloud parcel to travel from cloud base to the sampling level at -10°C . A longer interval (greater ratio) means more time available for the development of drops via coalescence. Applying this stratification greatly assisted the statistical analyses.

This classification technique echoes a result arrived at in a modeling study of seedability by Rokicki and Young (1978). They used updraft velocities and cloud-base temperatures to define areas of varying risk of overseeding with silver iodide (see their Fig. 4). Clouds with warm bases and weak updrafts were deemed difficult to overseed. Their model predicts that, while coalescence dominates in these clouds, silver iodide seeding still produces an echo earlier than in the natural case.

A change to a double-blind seeding procedure was made at the start of the third season. The paired lists of randomized seed/no-seed and sample/no-sample instructions were read into a read-only memory (ROM) in Pretoria, which was then sent to Nelspruit and installed in the Learjet computer. Case numbers were selected in sequence and fed into the computer, which was wired to activate the seeding bins or not, depending upon the instructions in the ROM. Thus, the pilots did not know whether seeding was taking place during seed/sample and no-seed/sample operations. A skirt was installed around the base of the seeding bins so that the mechanism driving the seeding system could not be seen. Additionally, a loud horn sounded when the seeding button was pressed, effectively masking the sound of the activated seeding system. Achieving a blind no-seed/no-sample decision was not possible. An orange light was illuminated on the mission controller's

panel for no-seed/no-sample cases, and the pilots were instructed accordingly.

The output from the sensors in the dry-ice chutes, along with the case numbers and treatment, was encoded on the data tape. This information was not available during the playback of the cloud physics measurements but could later be decoded using separate software.

Since knowledge of treatment could have been gained by examining the contents of the dry-ice seeding bins after landing, all dry ice was expelled on the descent after a mission by activating both the seeding drive systems and the horn.

c. Statistical analyses

The seeded and unseeded storm track properties are compared by calculating:

- minima,
- maxima,
- arithmetic means,
- geometric means,
- standard deviations, and
- skewness.

Seed minus no-seed differences were calculated for each of the above. Only the differences in means are used in the analyses in the following section.

Results from many past weather modification experiments have been clouded by convoluted statistical analyses. Many of these analyses were based upon questionable assumptions about the distributions of the response variables, and they ignored the well-known dependence of precipitation upon successive units (see Brillinger et al. 1978). These problems are obviated by using standard rerandomization techniques to assess the significance of the differences in mean storm track properties (Edgington 1988).

One of the problems that arises when analyzing so many variables (127 track property differences) is that if the variables have normal distributions, 10% of them (in the case of the track property differences, about 13) will be found statistically significant at the 10% level (p values of 10% or less) by chance alone. R. Gabriel (1986, personal communication) suggested that an "in house" confirmatory experiment be carried out during the 1986–87 season. Briefly, the concept was as follows. While it is perfectly possible for 13 out of the 127 track property differences to achieve high p values by chance in a single season, it is unlikely that the same 13 would repeat that performance in a second season, and even more unlikely for three successive seasons.

The following statistics appeared to be particularly sensitive to time-dependent analyses—that is, those analyses that compare track property differences at decision time to those same differences 10, 20, or 30 min after decision time.

Decision time is defined as the time at which the seed/no-seed decision was made ($t = 0$). The other concepts are defined as follows:

- P_o , track property at time $t = 0$;
- P_t , track property at time t ;
- $\max(P_t, P_o)$, P_t or P_o , whichever is greater;
- persistence, $(P_t - P_o)/\max(P_t, P_o)$ (after Tsonis et al. 1984);
- the "max ratio" statistic is a variation of the persistence statistic;
- P_m is the maximum value reached by a track property in the time window being considered; and
- max ratio, $(P_m - P_o)/P_m$.

The persistence statistic ranges between -1 and 1 , and the max ratio between 0 and 1 . Both of these statistics avoid the evaluation problems that are often associated with long-tailed distributions.

4. Results

a. Introduction

In the analyses that follow, the no-seed/sample and no-seed/no-sample storms are combined in a single no-seed category. This was done because of sample size limitations and an unavoidable selection bias that affected any analysis of the second tier split of the data.

A total of 106 experiments were conducted during the first two seasons of the experiment. Thirty-seven tracks were eliminated for the following reasons:

total number of experiments	106
no aircraft tracking	3
unable to identify case tracks	4
case (no-seed) that did not rain	1
cases that failed the 10–80-km range restriction	12
volume exceeded 750 km ³ at decision time	2
eliminated because $T_{ccl}/\Delta T_{500} < 2.0$	15
remaining	69
seed	32
no seed	37.

The mean values for the storm day and track properties listed in appendix B were computed for the 32 seeded and the 37 no-seed storms. The test statistic was the difference between the two mean values. For those properties exhibiting strongly positively skewed distributions, the geometric mean was used rather than the arithmetic mean.

b. Guarding against bias

The properties listed in Table 2 (see also appendix B) were used to signal possible inadvertent selection biases.

TABLE 2. Measurements used to monitor for selection bias and summary of analysis to detect possible selection bias.

Property	Description			
7	Mean range of storms from radar (km)			
9	Storm volumes at decision time (km ³)			
10	Peak reflectivities at decision time (dBZ)			
241	Average mixing ratio—lowest 60 mb (g kg ⁻¹)			
242	Temperature at CCL (°C)			
243	Buoyancy at 500 mb (°C)			
244	$T_{ccl}/\Delta T_{500}$ ratios			
245	Number of storm tracks			
246	Cumulative 3° area–time integrals (km ² h)			
247	Maximum storm volumes (km ³)			
248	Maximum rate of increase in storm volumes (km ³ s ⁻¹)			
249	Maximum cloud tops (m)			
250	Maximum reflectivities (dBZ)			
	No-seed	Seed	Difference (%)	<i>p</i> value
7	59.1	51.3	–13	1
9	158	181	14	73
10	42.0	44.8	7	77
241	12.7	12.3	–3	11
242	12.7	12.1	–5	13
243	3.9	3.6	–7	25
244	4.4	3.9	–12	21
245	52	59	14	82
246	1384	1549	12	57
247	1606	1445	–10	36
248	1.27	1.14	–10	28
249	14 998	14 336	–4	7
250	61.2	61.4	0	56

Percentage differences calculated as $[(\text{seed} - \text{no-seed})/\text{no-seed}] \times 100$.

It could be argued that the last three storm day properties (248, 249, and 250) could be affected by seeding. The others should not be affected. The scheme is designed to guard against a selection bias that would nullify the results of the experiment. For instance, if all of the seeded storms had occurred (by chance) on days when there were numerous storm tracks and all the no-seed storms on days when only a few storm tracks were recorded, a positive seeding response would have to be treated with great caution since most of the seeding had taken place on days when there was strong low-level convergence.

Table 2 displays the differences between these control properties calculated using standard rerandomization techniques. Note that the order of the *p* value is the reverse of normal usage (seed/no-seed difference is significant at a *p* value of 95, rather than at 5%). For storm property number 7, the no-seed storms were on average 8 km farther from the radar than the seeded storms. This difference in mean positions of the seeded and no-seed storms was significant at a *p* value of 1%. Will this range bias cause a serious bias in the evaluation of the storm track properties? The answer is probably not, as long as the test storms are kept within the 10–80-km range annulus. The no-seed storms are on

average occurring in wetter environments than the seeded storms (storm property 241). This difference is significant at a p value of 11%. Did this affect the results? If so, it would have biased the results against a successful outcome (positive seeding effect). The same argument can be applied to the difference in average storm tops, (storm property number 249) which is significant at 7%. We believe that it is important to scrutinize as many of these control properties as possible. As more experience with convective cloud experiments is accumulated, the important control properties should become recognized and incorporated in convective cloud seeding programs.

c. The confirmatory experiment

Listed in Table 3 are those differences in seed/no-seed track property differences that had p values that equaled or exceeded 90% (equaled or were less than 10%) in the combined analyses for the first two seasons and equaled or exceeded 70% (equaled or were less than 30%) in each separate seasonal analysis. The sensitivity of the analysis was increased by restricting the computations to the first 30 min after decision time since on average 80% of the seeding occurred in the first 20 min after decision time.

Time intervals of 10 min on either side of decision time and 20, 30, and 40 min after decision time were analyzed. The -10- to 0-min time window should reveal any pretreatment biases. Those track proper-

ties that appeared to respond to treatment after two seasons of experiments are listed in order of response in Table 3.

The first track property seen to respond to treatment is the vertical centroid, which can be thought of as the center of gravity of the storm. Next (0–20 min), the seeded storms exhibit greater rates of increase in heights of storm mass. In the 0–30-min interval after seeding the rain fluxes, precipitable water and the gross characteristics of storm mass, volume, and 3° areas all showed apparent seeding-induced changes.

The important features of this analysis are that

- biases are revealed by analyzing track property responses in the 10 min prior to seeding, and
- the serial progression of events is physically reasonable.

The track properties that were predicted to respond in a third season of seeding were chosen from Table 3. Track properties that exhibited a bias in the -10- to 0-min time interval were excluded (properties 81 and 119). Also, only one of a pair of highly correlated (>0.9) track properties was selected (32 and 88, 66 and 82). Although the selection of track properties for Table 4 was somewhat subjective, these properties were chosen and published before the 1986–87 season commenced (Dixon and Mather 1986).

Table 4 shows that all but one of the p values have either stayed the same or increased with the addition of

TABLE 3. Percentage differences between seeded and unseeded track properties, with associated p values in parentheses, for seasons 1984–85 and 1985–86.

Property No.	Property	Time interval (min)				
		-10 to 0	0 to 10	0 to 20	0 to 30	0 to 40
98	Vertical centroid – persistence	-30 (29)	76 (96)*	35 (85)		
155	Height Zmax – MROI	17 (72)		85 (99)	69 (99)	71 (99)
160	Height Zmax – maximum ratio	62 (91)		53 (91)	56 (93)	
164	Mass = $f(ht)$ – MROI	-4 (44)		120 (100)	78 (99)	78 (100)
66	Rain flux – MROI	18 (69)		53 (93)	46 (96)	42 (94)
65	Rain flux – maximum	39 (90)		39 (92)	36 (93)	
71	Rain flux – persistence	-14 (34)		135 (89)	108 (90)	
72	Rain flux – maximum ratio	7 (61)		41 (95)	29 (91)	
81	Precipitable H ₂ O – max	59 (94)		48 (92)	47 (93)	
82	Precipitable H ₂ O – MROI	16 (75)		49 (94)		
88	Precipitable H ₂ O – maximum ratio	-3 (43)		43 (95)		
165	Mass = $f(ht)$ – MROD	-6 (45)		46 (99)	27 (92)	
119	Reflectivity – maximum	3 (91)		4 (95)	3 (92)	
121	Reflectivity – mean	4 (93)		4 (95)	4 (97)	
149	Maximum height 45 dBZ – mean	7 (76)		21 (91)	26 (96)	
152	Maximum height 45 dBZ – persistence	-4 (42)			50 (94)	
32	Volume – maximum ratio	-9 (30)		39 (93)		
40	Mass – maximum ratio	-8 (31)		47 (95)	30 (91)	
50	3° area – MROI	9 (61)		44 (94)		
56	3° area – maximum ratio	7 (61)		26 (88)		

* Properties in bold were selected for the focus of the third-year experiment. Percentage differences are calculated as [(seed – no-seed)/no-seed] × 100.

TABLE 4. Significance (p) levels of percentage differences in various track properties for seasons 1984–85 and 1985–86; 1984–85 and 1985–86 combined; 1986–1987; and 1984–85, 1985–86, and 1986–87 combined.

	1984–85	1985–86	Combined	1986–87	Combined
Number of cases					
Seed	15	17	32	10	42
No-seed	20	17	37	15	52
Property No.	0–10 min				
98	72	97	96	80	96
0–20 min					
66	88	85	93	84	98
155	98	93	99	83	100
160	78	88	99	85	96
164	92	99	100	96	100
0–30 min					
32	84	90	93	72	96
50	88	79	94	97	98
65	84	81	92	84	96
66	94	79	96	92	99
71	92	78	89	79	95
72	82	85	95	87	98
121	91	83	95	74	94
149	77	86	91	79	93
155	86	96	99	86	100
164	77	99	99	90	100
165	94	89	99	83	99

the third (1986–87) season. The circled value indicates the p value that decreased.

The maximum rate of increase, maximum ratio, and persistence statistics seemed to respond most to seeding. They were the first to reflect differences between seeded and unseeded storms. One reason for this sensitivity may be that all three are independent of storm size.

At the end of the 1986–87 season, the time window analysis was further narrowed to 10-min segments after decision time. This was practical because a statistic that becomes highly significant after a given time tends to be dominant through subsequent time intervals. The track properties averaged over all three seasons that achieved a p value of 95% or more and the 10-min time windows in which this occurred are listed in Table 5. These statistics reveal a physically realistic chain of events.

At 0–10 min, seeded storms showed very strong increases in reflectivity at and above about 6 km. This could be a dynamic reaction (the sudden release of latent heat increasing the updraft, which is then capable of bringing more mass aloft, or alternatively, holding precipitation already forming aloft longer), a microphysical response (an increase in the number of growing precipitation embryos), or a combination of the two. Statistically, it is a very strong result. Properties

94, 98, 101, 106, and 164 (5 out of 8) achieved p values of 98% or better.

Between 10 and 20 min, the first indication of a change in rain flux appeared at cloud base (71 and 72). Also evident was a greater change in the rate of precipitation generation in the seeded storms (88). The other properties continued to indicate higher reflectivities at upper levels in the seeded storms (145, 152, 184).

Prior to the 20–30-min time interval, all but one of the radar-detected changes between the seeded and unseeded storms had appeared in the persistence, maximum ratio, or maximum rates of increase statistics. Now changes were seen in the maximum and the mean values. Most of these occurred in the reflectivity measurements.

In the 30–40-min time interval, the seeded storms were now producing significantly more rain than their unseeded counterparts (properties 67 and 68).

Perhaps the single most important result of the entire three-year experiment was the determination of the changes in the apparent response to seeding that were achieved after the storms were partitioned on the basis of their thermodynamic environments, as measured by local aircraft and radiosonde soundings. The effect of this partition on the outcome of the experiment is shown in Table 6. Only those storms that were pre-

TABLE 5. The p values exceeding 95% for storm track properties averaged over the three experimental seasons in 10-min time blocks after decision time.

0–10 min		10–20 min		20–30 min		30–40 min	
Property No.	Description	Property No.	Description	Property No.	Description	Property No.	Description
92	Mean mass – above 6 km	71	Rain Flux 3° – Persis.	35	Mass–Time Int.	23	Depth – Persis.
	Rain mass						
94	Centroid – MROI	72	Rain Flux 3° – M.R.	36	Mean Mass	67	Rain Mass – 3°
98	Centroid – Persis.	88	Precip H ₂ O – M.R.	65	Rain Flux 3° – max.	68	Rain Flux 3° – Mean
101	Z _{WT} Centr. – MROI	145	– Z > 6 km – Persis.	83	Perc. H ₂ O Time Int.	112	Centroid – Persis.
105	Z _{WT} Centr. – Persis.	152	H _{max} 45's – Persis.	94	Centroid – MROI	113	Centroid – M.R.
106	Z _{WT} Centr. – M.R.	184	dBZ = $f(\text{Ht})$ – MROI	119	Z _{max} – max	160	Ht Z _{max} – M.R.
155	Ht Z _{max} – MROI			121	Z _{max} – mean	223	% A = $f(\text{dBZ})$ – min
164	Mass = $f(\text{Ht})$ – MROI			126	Z – max		
				128	Z – mean		
				133	Z _{3°} – max		
				135	Z _{3°} – mean		
				140	Z _{6km} – max		
				142	– Z _{6km} – mean		
				147	H _{max} 45's – max		
				201	% V = $f(\text{dBZ})$ – mean		
				202	% V = $f(\text{dBZ})$ – max		
				222	% A = $f(\text{dBZ})$ – max		

dicted (based upon the $T_{\text{cel}}/\Delta T_{500}$ ratio) to stand a good chance of developing drops at the -10°C level are included in the second analysis in this table.

This analysis shows that there is a bias toward seeded storms of between 13% and 25% in the time interval prior to seeding. That these biases decrease proportionally or remain almost constant for three time intervals

for a total of 30 min suggests that they alone are not large enough to cause the two storm classes to behave differently.

Compared to the increase recorded 0–10 min after decision time, the percentage increase in average rain flux from seeded storms over that from no-seed storms had almost doubled in the 20–30-min time interval and

TABLE 6. Effects on three track properties of using the cloud-base temperature/buoyancy ratio to stratify the radar data, using the combined results from the three experimental seasons.

Stratification—Range: 10–80 km—Volume at decision time: 0–750 km ³					
Minutes	–10 to 0	0 to 10	10 to 20	20 to 30	30 to 40
Means					
Rain flux (%)	4	–3	–12	–18	17
Storm volume (%)	1	–3	–15	–11	8
Storm area (%)	2	–4	–8	–6	15
Cases					
Seed	47	51	49	47	38
No-seed	60	63	62	61	52
Stratification —Range: 10–80 km—Volume at decision time: 0–750 km ³ — $T_{\text{cel}}/\Delta T_{500} > 2.0$					
Minutes	–10 to 0	0 to 10	10 to 20	20 to 30	30 to 40
Means					
Rain flux (%)	25	15	17	38	76*
Storm volume (%)	18	15	19	26	43*
Storm area (%)	13	6	10	16	43*
Cases					
Seed	38	40	39	38	31
No-seed	46	48	47	47	39

* Significant at 0.05 or better.

All percentages calculated from $[(\text{seed} - \text{no-seed})/\text{no-seed}] \times 100$.

more than quadrupled in the 30–40-min interval after decision time. The percentage increase in storm volumes had only doubled over the same time interval. This suggests an increase in the efficiency of the rainfall process in the seeded storms. The relative increase in mean rain flux in the 20–30-min time interval can largely be accounted for by increases in reflectivities at scan angles of 3° ; that is, seeded storms produced more rainfall per unit area than their unseeded counterparts. By the 30–40-min time interval, the fourfold percentage increase in rain flux of seeded versus unseeded storms was accompanied by a similar increase in storm area.

The average seed and no-seed rain fluxes in 10-min intervals from decision time are shown in Fig. 1. Rain fluxes parallel each other for the first three time intervals. Thereafter, the no-seed rain fluxes decrease, while the seeded storm averages continue to increase into the 30–40-min time window.

Cumulative frequency distribution plots help determine the sizes of storms that appear to be responding to treatment. Such plots have the advantage of being able to detect a result dominated by one or two large storms. The cumulative distributions of rain flux from the seeded and the control storms are depicted in Figs. 2a and 2b for the 0–10- and 30–40-min time windows. Close to decision time, the two distributions are almost identical, indicative of the absence of a serious selection bias. By 30–40 min, the seeded and no-seed distributions are distinctly different. Half of the control storms are producing rain fluxes of $50 \text{ m}^3 \text{ s}^{-1}$ or more, while 50% of the seeded storms had fluxes greater than $100 \text{ m}^3 \text{ s}^{-1}$. Also, the separation of the two distributions 30–40 min after decision time suggests a reduction of rain fluxes from the medium-sized control storms, in addition to a transformation of seeded storms into higher rain flux categories. [All the distributions of the seeded and no-seed values of rain fluxes, rain masses, storm areas, and volumes are listed in Mather (1992)].

The strongest apparent responses to seeding (largest difference between seeded and no-seed storm tracks) occurred in the first 10 min following decision time in the radar-observed distributions of storm mass with height (Table 7). (Seeding took place within 2 min after decision time, and on average almost 50% of the seeding was accomplished in the next 8 min.) The radar-measured maximum rates of increase in storm mass with height responded strongly in the 0–10-min time window ($p = 100\%$) and less strongly in the next 10 min ($p = 95\%$), and then the measure of the maximum rates of *decrease* of storm mass with height reached significance ($p = 97\%$) 20–30 min after decision time.

In summary, the analyses show the following.

- In the first 10 min after decision time, radar measurements showing higher reflectivities aloft in seeded storms revealed an increase in the height of the center

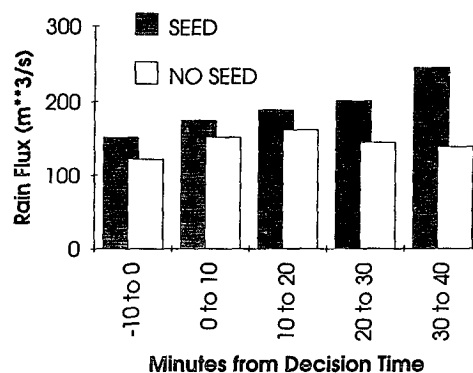


FIG. 1. Average rain fluxes from seed and no-seed storms in 10-min time windows from decision time.

of gravity in seeded relative to unseeded storms. This increase persisted into the 10–20-min period.

- The largest changes occurred in the low-level scan between 20 and 30 min after decision time. The first increases in rainfall were apparently caused by an increase in rain rate (reflectivity) rather than an increase in storm area.

- By 30–40 min after decision time, the seeded storms showed a fourfold percentage increase in rainfall and surface area coverage with respect to the control group of storms. The p values were used throughout to measure the magnitude of the differences between the mean track properties of the seeded and control storm groups. They cannot be considered to be tests of statistical significance since specific response variables were not prescribed prior to the commencement of the experiment (Brillinger et al. 1978).

d. Aircraft-produced ice crystals

Rangno and Hobbs (1983) suggested that APIPS could possibly contaminate the clouds used as controls in seeding experiments (if aircraft penetrated them). In an attempt to answer this question, the control clouds were subdivided into two classes: clouds that had been penetrated to obtain cloud physics samples and clouds that had not been touched by the aircraft. A large bias in favor of the sampled storms was easily detected by a control variable, track property 9 (volume at decision time), which indicated that on average the sampled storms were 88% larger than the untouched storms (p values of 100%), and by the predecision time values (–10 to 0) of rain flux and storm area. Table 8 shows that the sampled storm class produced 136% (p value of 98%) more rain than the storms that were not sampled, even before sampling had begun.

The successive increases in rain flux, storm volume, and area percentages were not nearly as large as those between the fourth and fifth time windows in Table 6, and only persisted into the 10–20-min window, a result consistent with the apparent sample bias but not with

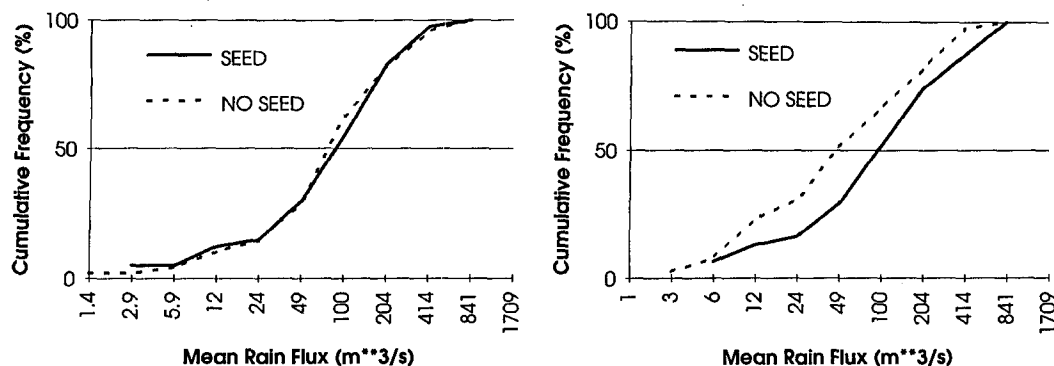


FIG. 2. (a) Relative cumulative frequency distributions of rain flux from seeded and no-seed storms in the 0–10-min time window. (b) Same as (a) but for the 30–40-min time window from decision time.

a treatment (APIPS) effect. This illustrates the usefulness of the time window analysis technique. It offers a record of storm track statistics suitable for comparing time-dependent variations in classes of convective clouds.

Much time was spent searching for statistical methods of adjusting the apparent bias encountered in this analysis, none of which were successful. This leaves open the question of the effects of APIPS upon clouds that are sampled but not seeded.

5. Discussion

a. Seeding hypothesis

The largest differences between seeded and unseeded storms were recorded during the first 10 min after decision time. The search for a seeding hypothesis will be confined to this period.

The observed change in mean rates of increase in storm mass with height between seeded and control storms may possibly be explained by one of three hypotheses.

1) The dynamic seeding hypothesis (Dennis 1980) suggests that the latent heat released by the sudden freezing of supercooled water dynamically invigorates the storm, strengthening updrafts that result in higher precipitation particle trajectories.

2) The static seeding hypothesis suggests that additional ice crystals are added to regions of the cloud where none, or only a few, exist naturally.

3) The freezing of drops hypothesis suggests that these frozen drops grow much faster as graupel than they would have had they remained unfrozen.

The Florida Area Cumulus Experiment, which was based upon the dynamic seeding hypothesis, did not produce the expected increases in rainfall during its final “confirmatory” phase (Woodley et al. 1983). The net increase in temperature caused by converting all supercooled water to ice is always less than 1°C (Lamb et al. 1981). Most of the clouds selected in the present experiment were naturally buoyant enough to push their cloud tops to the tropopause. The dynamic seeding hypothesis also predicts seeding-induced increases in cloud tops, a response not observed in our experiment.

A static seeding response leading to a significant increase in rainfall has been documented by the Israelis (Gagin and Neumann 1981). Measurements support the contention that ice crystals are essential for the formation of precipitation in Israeli clouds and that there is an insufficient number of natural ice crystals to promote efficient conversion of the available supercooled cloud water into rainfall. The introduction of silver iodide, which nucleates additional ice crystals, has apparently led to increases in rainfall.

While the static seeding concept may fit the Nelspruit results, the timing seems wrong. For ice crystals to grow large enough to start to rime and for riming growth (initially slow) to lead to graupel large enough to produce a radar echo is almost certain to take longer

TABLE 7. Percentage differences between radar-observed maximum rates of increase in mean storm mass with height in seeded versus no-seed storms, using data from all three seasons.

Minutes	–10 to 0	0 to 10	10 to 20	20 to 30	30 to 40
Mass = $f(\text{height})$					
Max rates of increase (%)	10	129*	66*	–10	3
Max rates of decrease (%)	–9	6	11	57*	8

* Significant at 0.05 or better.

TABLE 8. Comparison of no-seed/sample versus no-seed/no-sample cases.

Minutes	-10 to 0	0 to 10	10 to 20	20 to 30	30 to 40
Means					
Rain flux	136*	146*	207*	82*	79
Storm volume	52	96*	137*	89	78
Storm area	99*	81*	125*	36	63
Cases					
No-seed/sample	20	21	21	24	22
No-seed/no-sample	26	27	26	23	17

* Significant at 95% or better.

Percentages calculated from $[(\text{no-seed/sample}) - (\text{no-seed/no-sample})]/(\text{no-seed/no-sample}) \times 100$.

than 10 min. Furthermore, measurements of microphysical changes should not increase when applying the $T_{\text{cci}}/\Delta T_{500} \geq 2.0$ partition.

The third hypothesis seems to account for the observations. It follows Johnson (1987), who numerically tested the observation that graupel grew faster by riming than unfrozen drops did by coalescence (Braham 1964). The apparent greater rates of increase in storm mass with height in seeded storms can be attributed to freezing drops, which then follow a higher trajectory as graupel through the treated cloud. Of particular interest is the observation that the apparent response in this 10-min time window is enhanced when only those storms that stand a good chance of developing drops at the seeding level are considered. The larger graupel, upon melting, would produce higher radar reflectivities at low scan angles some 20 min after seeding (higher rain rates). The higher trajectories and wider distribution of fall speeds would also result in greater dispersion of the less dense graupel particles, spreading the precipitation from the seeded storms over a larger area (as observed 30–40 min after decision time).

The differential growth rates of frozen and unfrozen drops appear to explain most of the observed differences between seeded and unseeded storms in the Nelspruit randomized cloud seeding experiment. It is primarily the longer residence time in the clouds that leads to the graupel growing larger than the water drops, and it is this longer residence time that is responsible for the harvest of more water from the cloud, thereby increasing the efficiency of the precipitation process.

One puzzling observation from the three-year experiment was that seeded storms appeared to be moving faster than unseeded storms ($p = 94\%$). A possible explanation for this observation can be found in the drop freezing hypothesis. The higher trajectories of the drops frozen by the seeding would raise these particles into regions of higher wind speeds, causing the particles to precipitate farther downwind. This would appear to the radar as an increase in storm speed.

The confirmatory experiment was halted after a review of the experimental results at a workshop held in the Kruger National Park. Consensus was reached on the view that physical measurements supporting the

seeding hypothesis were required before the results of further statistical experiments could be accepted.

b. Comparisons to some other related experiments

Comparisons between the Nelspruit experiment and some of the major precipitation augmentation projects of the past are instructive, particularly for the purpose of designing future experiments.

In HIPLEX (Dennis et al. 1984) the goal was to gather between 50 and 150 test cases. During two field seasons, 48 clouds were declared treatment candidates. Of these, 20 passed the selection criteria determined from aircraft measurements collected on pretreatment passes (acceptance ratio of 42%).

In BPRP (Krauss et al. 1987) 113 clouds were declared test cases in a single season of operations; 60 were accepted as test cases (acceptance ratio of 53%).

Both the BPRP and HIPLEX experiments used the same experimental unit—semi-isolated cumulus congestus clouds. Both experiments detected significant increases in ice crystal contents in seeded versus control clouds based upon aircraft measurements.

In FACE II (Woodley et al. 1983) the goal was to gather between 35 and 60 days in three field seasons.

The experimental unit was the rain day. Evaluation of the experiment was based upon gauge-adjusted radar measurements of rainfall. A total of 61 cases (days) were gathered in three field seasons.

In the Nelspruit experiment 169 storms were declared treatment candidates in three field seasons; 94 were accepted as valid cases (for an acceptance ratio of 56%).

Both the FACE II and the Nelspruit seeding targets were similar—new clouds developing on the flanks of multicell storms. At Nelspruit, the experimental unit was the semi-isolated multicell storm; in FACE II it was the rain day. Although Nelspruit was not a confirmatory experiment (FACE II was, based upon the results of FACE I), it did show significant increases in radar-measured rainfall 20–40 min after decision time.

Although this is a subjective judgment, it would appear that as the evaluation unit moves upscale from cloud (HIPLEX and BPRP) to storm (Nelspruit) to

rain day (FACE), more experimental units are required to achieve statistically significant results. BPRP and HIPLEX were able to achieve statistical significance with 20–56 test cases. Nelspruit achieved apparent statistical significance at storm scales with around 94 cases. Since FACE II moved upscale from storms to the rain day as the evaluation unit, intuitively it seems unlikely that a statistically significant result could be achieved in less than 80 or so cases. In fact, a study by Flueck and Boik (1981, personal communication) indicated that 160 experimental days would be required to confirm a 23% increase in rainfall, which was the FACE I result.

The second Israeli randomized cloud seeding experiment required six seasons to collect 209 experimental days. The study showed positive increases in rainfall of between 13% and 18% at significant levels of 2.8% and 1.7%, respectively (Gagin and Neumann 1981). Based on a comparison of the FACE and Israeli experiments, it would appear that around 150 to 200 experimental days are required to substantiate rainfall increases of between 15% and 25% at acceptable levels of statistical significance ($<5\%$). This would require a commitment to an experiment lasting between 5 and 10 years. In most cases, it is not possible to get funding agencies to commit to such a long and costly field effort without offering them some hope of a successful outcome. That indication must come from trials that have led to rainfall increases from the entity that produces most of the rain on an experimental day. In the Nelspruit and FACE cases, this was the convective storm. But most importantly, the mechanisms that lead to the rainfall increase must be understood and documented, all the way from the initial introduction of the seeding material to more rain in the rain gauge.

6. Summary and conclusions

The results of the confirmatory experiment (section 4c) led to the rejection of the null hypothesis that there were no radar-measured differences between seeded and unseeded storms.

An objective storm tracking scheme was used. Storm track properties (127) were computed for seeded and unseeded storms, averaged, and the differences in their means compared. The best insight into the physical changes apparently caused by the seeding was the comparative analysis of these track properties in 10-min time windows on either side of decision time (–10 to 0, 0 to 10, 10 to 20, 20 to 30, and 30 to 40 min). Computations performed prior to decision time (–10 to 0 min) served as a check for inadvertent sampling biases. This type of analysis allows the use of time-dependent track properties: the persistence, maximum ratio, and maximum rates of increase statistics. These time-dependent statistics do appear to be the most sensitive to apparent seeding-induced changes, showing earlier seed/no-seed differences than the measurements of average storm volumes, areas, and rain fluxes.

The use of so many track properties, some of which are highly correlated, does complicate the analysis. However the track properties that reach acceptable levels of statistical significance (95%) are not doing so in a random fashion. There is a reasonable evolution of storm track property differences, from decision time to more radar-measured rainfall from seeded storms. These follow accepted physical principles. The analyses of this progression has led to the formulation here of a seeding hypothesis, which could be validated by future experiments.

The hypothesis of the third-year confirmatory experiment was that the storm track difference properties identified during two experimental seasons and listed in Table 3 were a result of the seeding. These properties were shown to also respond in a third season, and this led to acceptance of the hypothesis.

The successful outcome of this convective cloud experiment required the following:

- development of suitable hardware and software needed to run the research radar in a volume or sector scan mode;
- development of the software needed to analyze the radar data and to track storms through successive volume scans in order to define storms in terms of their track properties;
- identification of the key storm track properties that responded to seeding;
- ability to use aircraft safely and effectively in a severe storms environment to seed and to sample the microphysical characteristics of the experimental storms; and
- development of a simple thermodynamic scheme based on a local sounding, which separated clouds likely to develop precipitation via the coalescence processes from those favoring the ice phase route.

It was this last insight into cloud microphysical processes, revealed by the instrumented Learjet, that rescued this experiment from joining the ranks of the many inconclusive convective cloud seeding experiments.

Acknowledgments. This work would not have been possible without major contributions from the research team assembled at Nelspruit.

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APPENDIX A

Storm Properties

- | | |
|--------------|------|
| 1 Centroid X | (km) |
| 2 Centroid Y | (km) |

3 Centroid Z	(m)
4 Reflectivity-weighted centroid Z	(m)
5 Top	(m)
6 Base	(m)
7 Volume total	(km ³)
8 Volume <20 dBZ	(km ³)
9 Volume 20–25 dBZ	(km ³)
10 Volume 25–30 dBZ	(km ³)
11 Volume 30–35 dBZ	(km ³)
12 Volume 35–40 dBZ	(km ³)
13 Volume 40–45 dBZ	(km ³)
14 Volume 45–50 dBZ	(km ³)
15 Volume 50–55 dBZ	(km ³)
16 Volume 55–60 dBZ	(km ³)
17 Volume 60–65 dBZ	(km ³)
18 Volume 65+ dBZ	(km ³)
19 Area at 3°	(km ²)
20 Mean refl. at 3°	(dBZ)
21 Rain flux at 3°	(m ³ s ⁻¹)
22 Area at cutoff	(km ²)
23 Mean refl. at cutoff	(dBZ)
24 Rain flux at cutoff	(m ³ s ⁻¹)
25 Area at 3° < 20 dBZ	(km ²)
26 Area at 3° 20–25 dBZ	(km ²)
27 Area at 3° 25–30 dBZ	(km ²)
28 Area at 3° 30–35 dBZ	(km ²)
29 Area at 3° 35–40 dBZ	(km ²)
30 Area at 3° 40–45 dBZ	(km ²)
31 Area at 3° 45–50 dBZ	(km ²)
32 Area at 3° 50–55 dBZ	(km ²)
33 Area at 3° 55–60 dBZ	(km ²)
34 Area at 3° 60–65 dBZ	(km ²)
35 Area at 3° 65+ dBZ	(km ²)
36 Mass GL–2500 m	(kton)
37 Mass 2500–4000 m	(kton)
38 Mass 4000–5500 m	(kton)
39 Mass 5500–7000 m	(kton)
40 Mass 7000–8500 m	(kton)
41 Mass 8500–10 000 m	(kton)
42 Mass 10 000–11 500 m	(kton)
43 Mass 11 500–13 000 m	(kton)
44 Mass 13 000–14 500 m	(kton)
45 Mass 14 500–16 000 m	(kton)
46 Mass 16 000–17 500 m	(kton)
47 Mass 17 500+ m	(kton)
48 Peak refl. GL–2500 m	(dBZ)
49 Peak refl. 2500–4000 m	(dBZ)
50 Peak refl. 4000–5500 m	(dBZ)
51 Peak refl. 5500–7000 m	(dBZ)
52 Peak refl. 7000–8500 m	(dBZ)
53 Peak refl. 8500–10 000 m	(dBZ)
54 Peak refl. 10 000–11 500 m	(dBZ)
55 Peak refl. 11 500–13 000 m	(dBZ)
56 Peak refl. 13 000–14 500 m	(dBZ)
57 Peak refl. 14 500–16 000 m	(dBZ)
58 Peak refl. 16 000–17 500 m	(dBZ)
59 Peak refl. 17 500+ m	(dBZ)
60 Mean reflectivity	(dBZ)

61 Peak reflectivity	(dBZ)
62 Height of peak reflectivity	(m)
63 Max height of 45-dBZ echo	(m)
64 Left open for track No.—during the running of this routine this slot is used to keep track of the total number of volumes that comprise the storm.	

Notes on storm properties

(i) A storm is defined as any contiguous volume all of which exhibits reflectivities in excess of a threshold value, in the case of this study, of 30 dBZ. A minimum volume of 3 km³ is set, so that the tracking program will commence (cease) tracking a storm whose reflectivity and volume exceed (decrease below) 30 dBZ and 3 km³.

(ii) Reflectivity-weighted centroid Z. This is the vertical center of gravity of the storm weighted with respect to reflectivity. Property 3 is purely a geometric property. Should property 4 be lower than 3, then the storm is bottom heavy with respect to reflectivity.

(iii) Cutoff altitude (CO). This is set at 6 km above sea level and chosen because radar data at or above 6 km is reasonably uniform with range (3° properties, the lowest scan level, will be more range dependent). Also, seeding occurs at approximately this level.

(iv) Rain flux. Computed using (Marshall and Palmer 1948) $Z_e = 200R^{1.6}$, where Z_e is effective radar reflectivity factor (mm⁶ m⁻³) and R is rain rate (mm h⁻¹).

(v) Storm mass. Computed using (Morgan and Meuller 1972) $M = 2.634 \times 10^{-3} Z_e^{0.6}$, where M is storm water mass (g m⁻³).

(vi) Max height of the 45-dBZ echo. This property is regarded as a hail indicator and signals a risk of hail if it exceeds 7.5 km.

APPENDIX B

Storm Track Properties

a. Group 1—Geometry, time	
1. Duration (h)	
2. Time of origin (SAST)	
3. Speed of movement (km h ⁻¹)	
4. Direction of movement (°)	
5. Mean x coordinate (km)	
6. Mean y coordinate (km)	
7. Mean range (km)	
8. Decision time (DT) SAST	
9. Storm volume at DT (km ³)	
10. Peak dBZ at DT	
b. Group 2—Storm top, depth, volume, mass	
Maximum:	Track Property
(a) Echo top (m)	11
(b) Storm depth (m)	18
(c) Storm volume (km ³)	25
(d) Storm mass (kton)	33
(e) Storm mass above 6 km (kton)	41

Maximum rates of increase in:

(a) (m s^{-1})	12
(b) (m s^{-1})	19
(c) ($\text{km}^3 \text{s}^{-1}$)	26
(d) (kton s^{-1})	34
(e) (kton s^{-1})	42

Time integral of:

(c) ($\text{km}^3 \text{h}$)	27
(d) (kton h)	35
(e) (kton h)	43

Mean:

(a) (m)	13
(b) (m)	20
(c) (km^3)	28
(d) (kton)	36
(e) (kton)	44

Persistence of:

(a)	16
(b)	23
(c)	31
(d)	39
(e)	47

Maximum ratio of:

(a)	17
(b)	24
(c)	32
(d)	40
(e)	48

c. Group 3—Storm areas, rain fluxes, precipitable water

Maximum

(f) Storm area (km^2)	49
(g) Storm area at 6 km (km^2)	57
(h) Rain flux at 3° ($\text{m}^3 \text{s}^{-1}$)	65
(i) Rain flux at 6 km ($\text{m}^3 \text{s}^{-1}$)	73
(j) Precipitable water (kton)	81

Maximum rates of increase in:

(f) (km^2)	50
(g) ($\text{km}^2 \text{s}^{-1}$)	58
(h) ($\text{m}^3 \text{s}^{-2}$)	66
(i) ($\text{m}^3 \text{s}^{-2}$)	74
(j) (kton s^{-1})	82

Time integral of:

(f) ($\text{km}^2 \text{h}$)	51
(g) ($\text{km}^2 \text{h}$)	59
(h) (kton)	67
(i) (kton)	75
(j) (kton h)	83

Mean:

(f) (km^2)	52
(g) (km^2)	60
(h) ($\text{m}^3 \text{s}^{-1}$)	68

(i) ($\text{m}^3 \text{s}^{-1}$)	76
(j) (kton)	84

Persistence of:

(f)	55
(g)	63
(h)	71
(i)	79
(j)	87

Maximum ratio of:

(f)	56
(g)	64
(h)	72
(i)	80
(j)	88

d. Group 4—Vertical centroids

Maximum:

(k) Vertical centroid (m)	93
(l) Reflectivity weighted vertical centroid (m)	100
(m) Δ Vertical centroid (m)	107

Maximum rates of increase in:

(k) (m s^{-1})	94
(l) (m s^{-1})	101
(m) (m s^{-1})	108

Mean:

(k) (m)	95
(l) (m)	102
(m) (m)	109

Persistence of:

(k)	98
(l)	105
(m)	112

Maximum ratio of:

(k)	99
(l)	106
(m)	113

e. Group 5—Reflectivities

Maximum:

(n) Peak reflectivities (dBZ)	119
(o) Mean reflectivities (dBZ)	126
(p) Mean reflectivities— 3° (dBZ)	133
(q) Mean reflectivities—6 km (dBZ)	140
(r) Maximum height—45 dBZ (m)	147
(s) Height peak reflectivity (m)	154

Maximum rates of increase in:

(n) (dBZ s^{-1})	120
(o) (dBZ s^{-1})	127
(p) (dBZ s^{-1})	134
(q) (dBZ s^{-1})	141
(r) (m s^{-1})	148
(s) (m s^{-1})	155

Mean:

(n) (dBZ)	121
(o) (dBZ)	128
(p) (dBZ)	135
(q) (dBZ)	142
(r) (m)	149
(s) (m)	156

Persistence of:

(n)	124
(o)	131
(p)	138
(q)	145
(r)	152
(s)	159

Maximum ratio of:

(n)	125
(o)	132
(p)	139
(q)	146
(r)	153
(s)	160

f. Group 6—Storm mass and reflectivity as a function of storm height

Mean:

(t) Storm mass = $f(\text{height})$ (m)	161
(u) Reflectivity = $f(\text{height})$ (m)	181

Maximum:

(t) (m)	162
(u) (m)	182

Minimum:

(t) (m)	163
(u) (m)	183

Maximum rates of increase in:

(t) (m s^{-1})	164
(u) (m s^{-1})	184

Maximum rates of decrease in:

(t) (m s^{-1})	165
(u) (m s^{-1})	185

g. Group 7—Storm volume and area as a function of reflectivity

Mean:

(v) % Storm volume = $f(\text{dBZ})$ (dBZ)	201
(w) % Storm area = $f(\text{dBZ})$ (dBZ)	221

Maximum:

(v) (dBZ)	202
(w) (dBZ)	222

Minimum:

(v) (dBZ)	203
(w) (dBZ)	223

Maximum rates of increase in:

(v) (dBZ s^{-1})	204
(w) (dBZ s^{-1})	224

Maximum rates of decrease in:

(v) (dBZ s^{-1})	205
(w) (dBZ s^{-1})	225

h. Group 8—Storm day measurements

241. Average mixing ratio—surface to 60 mb
(g kg^{-1})
242. CCL temperature— T_{CCL} ($^{\circ}\text{C}$)
243. Buoyancy at 500 mg— ΔT_{500} ($^{\circ}\text{C}$)
244. $T_{\text{CCL}}/\Delta T_{500}$
245. Number of storm tracks for the day
246. Cumulative 3° area—time integral for the day
($\text{km}^2 \text{ h}$)
247. Maximum storm volume recorded (km^3)
248. Maximum rate of increase in storm volume
($\text{km}^3 \text{ s}^{-1}$)
249. Maximum echo tops recorded for the day
(m)
250. Maximum reflectivities recorded (dBZ)

Notes on storm track properties

(i) Storm depth, properties 18–24. Storm top minus storm base. Tends to be somewhat range dependent because of 3° low-level scan angle.

(ii) Precipitable water, properties 81–88. This is an estimate of the amount of precipitable water in the storm at any time. It is computed by adding the storm mass to the (rain flux) $\times$ (scan time interval). Changes in precipitable water should give an indication of the rate of precipitation generation.

(iii) Reflectivity-weighted vertical centroid, properties 100–106. Vertical storm centroid weighted with respect to reflectivity (properties 93–99 are computed geometrically with respect to volume).

(iv) Delta vertical centroid, properties 107–113. Calculated from (volumetric vertical centroid) – (reflectivity weighted centroid). A negative value indicates that a storm is bottom heavy with respect to reflectivity.

(v) Peak and mean reflectivities, properties 119–132. Computed from reflectivities in the entire storm volume.

(vi) Mean dBZ 3° and mean dBZ cutoff, properties 133–146. Computed at 3° and at 6 km (the cutoff level), respectively.

(vii) Mass = $f(\text{height})$, properties 161–165. Computed from the distribution of storm mass with height. This is not a statistical distribution, but statistical computations are used to give an indication of the shape of this distribution. Therefore, the mean of the means, maxima, and minima of this distribution are computed. Also the mean of all the maximum rates of increase and decrease of the mean distribution of mass with height

is computed for selected storms over the time period of interest.

(viii) $\text{dBZ} = f(\text{height})$, properties 181–185. The distribution of maximum reflectivity with height [see (vii) above].

(ix) % storm volume = $f(\text{dBZ})$, properties 201–205. This is a density function of the distribution of reflectivity within the storm volume. The mean storm volume in the reflectivity intervals in appendix A, storm properties 8–18, are computed at each scan time as well as the mean maximum rates of increase and decrease in the mean storm volumes over the period of interest.

(x) % storm area = $f(\text{dBZ})$, properties 221–225. The distribution of storm area at the lowest scan angle (3°) in the reflectivity intervals shown in appendix A, storm properties 25–35 [see (ix) above].

(xi) MAXROI (MAXROD). These refer to the maximum rates of increase (decrease) in the storm track property considered over the time period of interest. Those properties that are believed to have exponential growth and decay characteristics are storm volume, mass, area, rain flux, and precipitable water. These properties are fitted with exponential growth and decay profiles over time periods of interest. All other track properties are fitted with linear growth profiles.

(xii) Inspection of the track property histograms has led to the classification of the properties into log (for lognormal distributions with high positive skewness) and linear groups.

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