"REVIEWED"

PRELIMINARY RADAR RESULTS FROM THE 1984/85 SEEDING EXPERIMENT

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1. Introduction

The Programme for Atmospheric Water Supply (PAWS) has as its initial objective the determination of the feasibility of augmenting rainfall in the Nelspruit region. The experimental philosophy follows that of the High Plains Experiment (HIPLEX 1) in which each step leading to additional precipitation will be verified by observations during the course of the experiment.

The first step which may lead to a precipitation change is the ability to alter the cloud microphysics in a predictable and repeatable manner. This entails a search for a suitable seeding material. The desired microphysical response must be measurable with available equipment. As in the HIPLEX 1 experiment, field tests led to the choice of dry ice as the seeding material. It was found that dry ice seeding of cumulus congestus clouds produced more ice crystals spread over a larger area (better dispersion) than similiar tests with silver iodide flares. Some of the reasons for these results have been clarified by the laboratory work of Morrison et al (1984) in the Isothermal Cloud Chamber at Colorado State University (Reference 1).

The next step is to see if the microphysical changes that are observed at aircraft volume sampling scales (litres), spread to scales large enough to be detected by radar (km³). For it would seem that if cloud seeding is to produce significant additional rainfall from treated clouds, then the changes that follow seeding should be observable by sensitive radars.

As part of the PAWS project a randomized cloud seeding programme was designed to detect such changes. This note reports on the design and results from the first season's experiment.

2. Target Selection

The selected target for the experiment is the medium size, isolated multicellular storm. This target was chosen for several reasons :

- this entity can be readily identified by a storm tracking programme
- the medium-sized convective complex is almost always present on a convective day thus supplying many target opportunities
- historical studies indicate that the selected target is significant in terms of rain production in the Nelspruit area (Reference 2).
- the convective complex is large enough to provide a longer lasting source of supercooled water than that found in the HIPLEX 1 clouds (Reference 3).

3. Experimental Design

Randomization is recognised as the only reliable cure to many experimental problems, and has been adopted in the design of the Nelspruit exploratory experiment. Concern about aircraft-produced ice particles and their possible effects on untreated storms led to a three way randomization (seed/sample, no seed/sample, no seed/no sample). In this analysis, the no seed/sample and no seed/no sample cases have been combined because of the limited size of the data set.

Since the radar-measured variables that might be expected to reflect a seeding related change are not known, this first randomized experiment is exploratory. The distinction between an exploratory and a confirmatory experiment is important. Some of the purposes of an exploratory experimental phase are:

- to determine those situations in which seeding will be more effective
- to learn how to better measure the effects
- to identify the strongest radar (and other) response variables
- to gain a clearer understanding of cloud physics and cloud processes.

Ideally, the exploratory phase will identify responses which are repeatable, thereby justifying a confirmatory experiment.

4. Data Analysis

Radar data are acquired by running the Nelspruit 5 cm radar under computer control in a volume scan mode. The elevation sequence allows acquisition of data from within an annular volume bounded horizontally by the 10 to 130 km radar range rings and vertically by a surface 20 km above mean sea level. The raw integrated video from the radar was stored on magnetic tape and analysed in the following way:

(i) The raw video was dumped to disk.
(ii) A programme called "Storms" was used to process the raw radar data, computing a total of 63 instantaneous storm properties.
(iii) A storm tracking programme (Reference 4) computes storm tracks from an analysis of the storm properties.
A total of 54 track properties are computed for each track. For the identified case tracks, an additional 11 properties are calculated which are keyed to the applicable seed/no seed decision time.

Six "day" properties are also computed and used to categorize the experimental day. Indications of biases that might arise from a series of "bad draws" should be revealed by these properties. Two additional day properties (a measure of cloud buoyancy and surface moisture) are derived from the aircraft sounding.

(iv) Case tracks are identified by plotting all storm tracks close to the track plot of the Learjet at the time of treatment. In all cases, unambiguous identification of the storm case track was achieved once the recording of the aircraft transponder return with the radar data had been implemented.

A total of 49 seed/no seed experiments were performed in the 1984/85 season. Twelve of the 49 were rejected leaving 37 tracks for further analysis, 16 seed and 21 no seed.

Certain tracks and storms were rejected for the following reasons:

(i) No aircraft tracking: It was found at the outset that storm tracks could not be unambiguously identified without aircraft track information. Operations were suspended until the recording of the aircraft transponder and radar data could be recorded simultaneously.

This was achieved by 26 October 1984.

(ii) Day too active: Some days that produced widespread storm activity were deleted from the analysis for two reasons. On such days, the storm tracking programme produced huge track properties as the tracking programme picked up storms that merged into squall lines that swept through the area. Looking for a potential radar seeding signature on such days is probably unrealistic. Secondly, including these days in the analysis produced biases in the control properties. All days on which the cumulative 3 degree area-time integral exceeded 2500 km hr were thus not incorporated in this analysis.

(iii) No valid track: Case tracks that did not persist for 24 minutes or longer were also rejected.

(iv) Seeding at the wrong temperature: The operations plan calls for seeding between -10 and -15 degrees C. On 12 November 1984, the real time display of static temperature was not available to the crew and seeding was conducted at around -25 degrees C.

5. Statistical Analyses

For the 16 seed and 21 no seed cases, the following statistics were calculated for each of the 73 track properties:

- minima
- maxima
- arithmetic means
- geometric means
- standard deviations
- skewness
- inter-property correlations (73x73)

The test statistic for each of the above was defined as the (seed) minus the (no seed) difference.

The significance of the differences was determined using standard re-randomization techniques (Reference 5). Difference distributions were generated by randomly drawing 16 pseudo seed cases out of the 37 case pool using the same randomization scheme used for the real draw. If p % of the differences calculated by the re-randomization are equal to or more extreme than the values obtained in the real experiment, then p % is an appropriate measure of the unlikeliness of the actual result.

For example, if the difference in mean cloud heights between the seed and no seed cases falls within the top (or bottom) 50 differences calculated from 1000 re-randomizations then p will be equal to or greater than 95 percent (or less than 5 percent).

6. Preliminary Results

Preliminary results while not highly significant show trends in the direction of :
(i) Seeded storms producing more radar-estimated rainfall than unseeded storms
(ii) Seeded storms averaging stronger reflectivities at 3 degrees

Table 2: Some Trends in the Analysis to date

No	Property Description	Change (%)	P(%)	Statistic
31	Mean 3° rain flux	30.1	85	Geom. Mean
46	Mean 3° reflectivity	2.7	94	Arith. Mean

(iii) Differences between seed and no seed time-dependent properties (Table 3). Here decision time is that time at which the pilot of the Learjet receives a seed/no seed decision from radar.

Table 3 : Time - dependent Properties.

No	Property	Change (%)	P%	Statistic
59	Max. rate of increase in Mass 5-30 min after decision time	854	91	Geom. Mean
63	Max rate of increase in rain flux 5-30 min after decision time	748	89	Geom. Mean

It is usually advisable to construct plots of the properties that appear to be responding to treatment, to guard against being led astray by quirks in the distributions (gross outliers, etc). Comparative cumulative seed/no seed distributions of properties 46, and 63 are shown in Figs. 1 and 2.

Another comparison of interest is the seed versus no seed time from decision to maximum rate of increase in mass (Fig. 3). Although the p statistic does not show significance, the seed distribution of this variable peaks after the decision time, whereas the no seed peaks before. This sort of analysis suggests that a closer look at these and other track properties as they relate to the onset of seeding may provide useful insights into the physical changes accompanying treatment.

The correlation difference analysis may be even more revealing in terms of changes in physical processes between the seed and no seed cases. Preliminary results are presented in Tables 4 and 5 below:

Table 4 : Changes in Correlation of Volume vs Mass

No	Properties Description	Correlations Seed	No Seed	Season	P(%)
12	Max Volume	0.90	0.98	0.98	0
36	Max Mass				
14	Vol Time Integral	0.98	0.99	0.99	1
38	Mass " "				

Table 5 : Changes in Correlation of Area vs Rain Flux

No	Properties Descriptions	Correlations Seed	No Seed	Season	P (%)
23	Mean 3° area	0.93	0.98	0.96	3
31	Mean 3° rain flux				
46	Mean DBZ at 3°	0.35	0.85	0.83	3
22	3° Area time integral				

The season correlations shown in Table 4 and 5 are obtained from 1478 non-case storm tracks collected throughout the season, and differ little from the corresponding non-seed track correlations, lending support to the noted seed/no seed differences.

Since storm masses are computed from

$$Z = 2.03 \times 10^{4} M^{1.67} \qquad (1)$$

and rain fluxes from

$$Z = 200 R^{1.6} \qquad (2)$$

where :

Z is radar reflectivity (mm^6/m^3)
M is mass (grams / m^3)
R is rain rate (mm/hr)

the changes suggest that seeding is affecting either the radar-measured reflectivities or the storm volumes and areas (which are delimited by the 30 dbz contour). Preliminary evidence (increases in mean dbz at 3°) suggest the former.

In summary, the results of one season's seeding suggest that :

(i) Seeding is tending to produce more radar-estimated rainfall from storms with higher 3 degree radar reflectivities.

(ii) Properties measured 5 to 30 minutes after decision time (maximum rate of increase in mass and rain flux) show changes between the 16 seed and 21 no seed cases.

(iii) Seeding is affecting storm reflectivities, indicated by changes in volume/mass and rain flux/area correlations.

7. Discussion

Certainly, one of the purposes of an exploratory experiment is to develop measurement techniques. One of the main aims of the current experiment is to develop methods of measuring radar responses to glaciogenic seeding of medium-size multicellular storms. Initial results are promising. Additional work is required in the following areas:

(i) Confirmation and refinement of the current statistical techniques.
(ii) A continuing search for more meaningful radar response variables.
(iii) Integration of the aircraft cloud physics data with the radar measurements. It is clear that changes in radar measurements must be related to changes in physical processes that are occurring in the treated clouds. Unless the observed radar changes are physically plausible in terms of a reasonable seeding hypothesis, they must be treated with suspicion.
(iv) Development of the capability in the cloud base aircraft to measure rain areas, rain rates and radar reflectivities at cloud base.

8. Conclusions

Preliminary results indicate that one of the goals of this experiment, the recognition of seeding-induced changes in radar-measured storm properties, can be achieved. It is extremely important at this stage that:

- the experiment continue for at least another season
- the experimental design remain unchanged.

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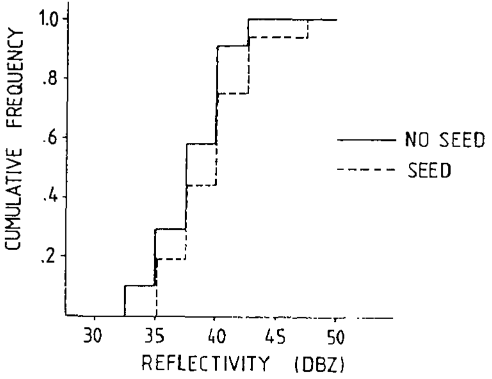

Fig.1: Cumulative comparison of mean 3 degree radar refectivities of seed versus no seed storms.

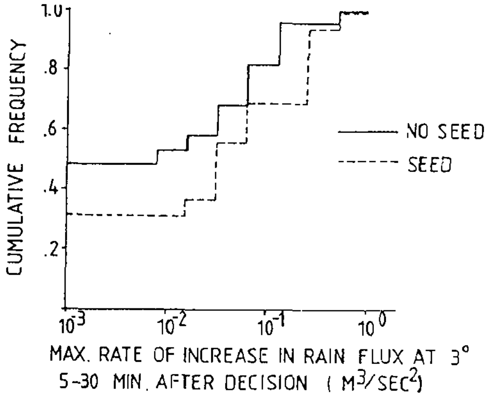

Fig. 2: Cumulative comparison of maximum rates of increase in 3 degree rain fluxes, 5-30 minutes after seed-no seed decision.

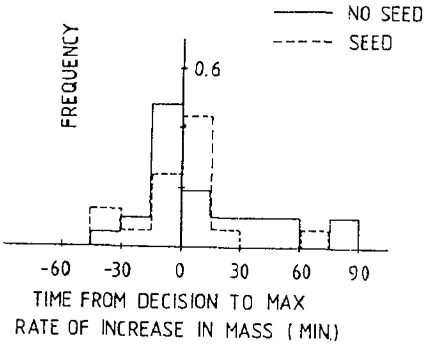

Fig.3 : Distribution of maximum rates of increase in storm mass with respect to seed-no seed decision times.