"REVIEWED"

PAWS RESTRUCTURED

R C GROSH (PAWS Scientific Director, Rain Stimulation Project Leader)
C MÜLLER (Rain Stimulation)
J GALPIN (Centre for Advanced Computing & Decision Support
I AURET (Centre for Advanced Computing & Decision Support)
M C HODSON (Rain Measurement, Project Leader)
D E PROCTOR (Lightning Probing, Project Leader)
G REUTER (Weather & Industry, currently with McGill Univ., Canada)
D vdS ROOS (Weather & Industry, Programme Manager)

CSIR
P O Box 395, PRETORIA 0001 South Africa

INTRODUCTION

The Program for Atmospheric Water Supply (PAWS) is a randomized summer rain stimulation experiment utilizing dry ice released by Learjet as the seeding agent. Seeding is done during penetration into growing turrets of convective storms at the -10°C level. The main goal of the PAWS is to increase the water supply to all the people living in the dry climate of South Africa, but particularly to the Eastern Transvaal where rapid industrial and population growth will require additional water within the next generation. The experiment is now examining the physical effects of seeding on individual cloud systems. In the future, it is expected that statistical evaluations will be carried out over predetermined areas on the ground. The PAWS study has been on-going since 1981 and is partially described in Grosh (1988a), Dixon and Mather (1986), Morrison *et al.* (1986) and Mather *et al.* (1986), where initial radar and airborne microphysical analyses are briefly discussed. A series of lengthy annual reports supplies more complete and current information (Grosh, 1988b).

Funding and general management are provided by the Corporation for Atmospheric Water Supply (CRAWS). In January 1987 scientific direction for the project was placed in the hands of CSIR, a national science institute, to reduce the dependence on and expense of foreign consulting firms, to develop local expertise, to expand the investigations, and to begin the process of independent confirmation of the very promising initial results. The importance of a

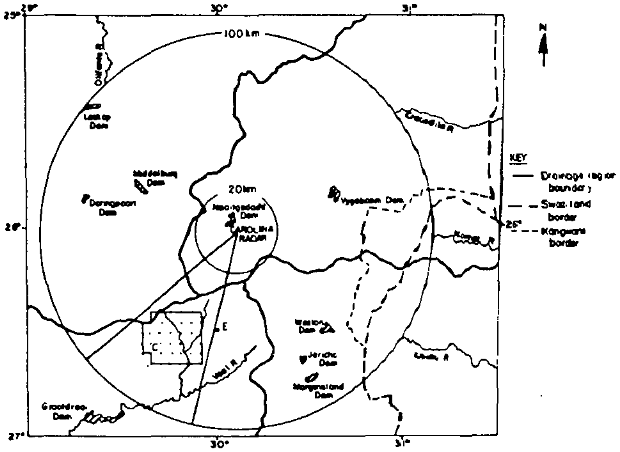

Figure 1: The new PAWS rain gauge network.

supporting institution with a broad scientific base to successful rain stimulation projects is discussed in Grosh (1989). Independent statistical analysis was contracted for within CSIR (Galpin, 1988) and preliminary cloud modelling undertaken at that time.

In 1988 a new scientific director was appointed within CSIR. At this point, three originally independent CSIR scientific projects also began to contribute to the rain stimulation studies through the office of the scientific director. These dealt with radar rainfall measurements, lightning locations, and investigations of ice particles in a coldroom laboratory. Thus, the project now has seven major components: scientific director, field operations (mainly CloudQuest), statistical analyses, rain measurement, electrical probing, laboratory studies, and cloud modelling. The purpose of this note is to describe the early stages of the CSIR development process, and the current state of the expanding project.

Field Equipment

The primary evaluation of PAWS is provided by the project radar which radiates at 5 cm wavelength and performs a fully digitised three-dimensional volume scan every 7 or 8 minutes. Recently the radar site has been moved to Carolina, about 110 km to the southwest of its original location at Nelspruit (Figure 1). The move was made to obtain improved viewing geometry and to be closer to the hydrologic centroid of the Eastern Transvaal. Plans are underway to expand the new rain gauge network to forty gauges, and improvement of the project radar facilities (to 10 cm) is thought likely to occur soon as well.

Two aircraft now serve the project, an Aerocommander for cloud base studies and a very maneuverable Learjet for seeding and penetration studies. The Learjet utilizes the 2D-C, FSSP, and King Hot Wire probes, amongst others. In addition, the jet engine is used as the evaporator in the first stage of a Lyman-alpha total water meter. The cloud base plane is equipped with a 2D-P probe. The nose radars of both planes are being developed for quantitative precipitation studies. All these facilities are maintained and operated by a commercial subcontractor, CloudQuest, which has been with the project since its inception.

The development of the jet engine evaporator/total water meter is one of the principal accomplishments of the PAWS project. Its main advantage over earlier total water meters is its very large sample volume, 15 m^3/sec (Morgan *et al.*, 1986; Kyle, 1975; Grosh, 1988a).

The two subprojects dealing with electrical effects on precipitation growth and radar rainfall measurements have additional special equipment including four radars (one a vertically pointing Doppler, one a long-wave lightning detector), several distrometers and rain gauges and an array of five VHF radio receivers for determining the location of lightning discharges. However, these are not located in the seeding area.

CloudQuest

In addition to field operations, CloudQuest has always played a strong role in planning and evaluating the PAWS experimental activities. One of the main contributions has been the identification of the very useful stratification variable, the coalescence time parameter. When the ratio of the cloud base temperature to the 500 mb temperature buoyancy is greater than two, coalescence drop growth is relatively favoured by the long time available for collisions as the cloud air rises slowly toward the -10°C flight level. The Learjet 2D-C observations confirm the effectiveness of this parameter in identifying conditions in which coalescence is dominant, as indicated by encounters with large droplets (>300 µm) at the -10°C level. The main use of this parameter is in analysis of the PAWS radar data. Early indications suggest that when large droplets are present at the seeding level, seeding effects on storm size and rain are more likely to be significant. In other words, a "dynamic" seeding effect receives some support in the Eastern Transvaal.

Laboratory

A 23 m^3 coldroom (-10°C) is being obtained for cloud physic studies, such as of the" ice whiskers" associated with the dry ice seeding pellets. A small vertical wind tunnel is also available.

Lightning Probing

The programme of lightning research is carried out at a field station near Johannesburg. Paths of lightning flashes are traced by locating the sources of radio noise emitted by the flashes themselves. This is done by measuring the differences in the times of arrival of noise at the 5 widely spaced VHF receivers. The noise is retransmitted over microwave-lengths to the main station where it is recorded on a laser optical recorder which can record 5 channels, each with a bandwidth of 6 MHz for an uninterrupted duration of 20 min.

These observations are supplemented by recordings of electrical field changes, by means of which the type of flash can be identified. In many cases the field-changes can be used to compute the current that flowed in the channel as well as the charge that was carried by a streamer, because its path is known. However, in order to do this it is necessary to assume the form of the charge distribution. The form of the charge distribution is not critical but the measured wave form cannot be regenerated from the data if a point distribution is assumed.

The Learjet will conduct limited studies in this network to determine if the meteorological conditions (draft structure, water contents) associated with the lightning locations can be ascertained.

Rainfall Measurement Usage

This investigation concentrates on finding the reasons for the differences in radar measured rainfall aloft and gauge measured rainfall at the ground using two different approaches, modelling and observation. A 9.3 GHz vertically pointing Doppler radar with eight nearby rain gauges and two anemometers are used to make observations.

Amongst several factors which change the rainfall structure with altitude, the combination giving the largest differences between rainfall aloft and at the ground appears to be the horizontal wind and differential drop fall velocities. Modelling these shows that differences in the rainfall rate of up to 100% can be obtained over a 600 m fall. An example of the output from a simple model for still air which uses measured rainfall rates as input is given in Figure 2. Here the maxima aloft and at the ground differ by 19%. In addition to amplitude reductions, phase shifts are also common. Both will become worse the higher the point of origin (radar observation level) is above ground. Testing these models by applying them to the Doppler radar measurements is currently being undertaken.

Few studies have dealt with the actual causes of the discrepancies in radar rain measurements. Thus, it is believed that this subproject will help determine the most efficient means of measuring surface rains when PAWS requires areal rain measurements.

Statistical Analyses

Full independent statistical and physical evaluations of the seeding effect on the PAWS storms will come only with time to resolve conflicts in sampling and statistical analysis procedures between CSIR and CloudQuest and to ponder the physical circumstances. For now, the seven radar variables (out of 250 available radar variables) which intuition tells us are the most closely related to the rain producing

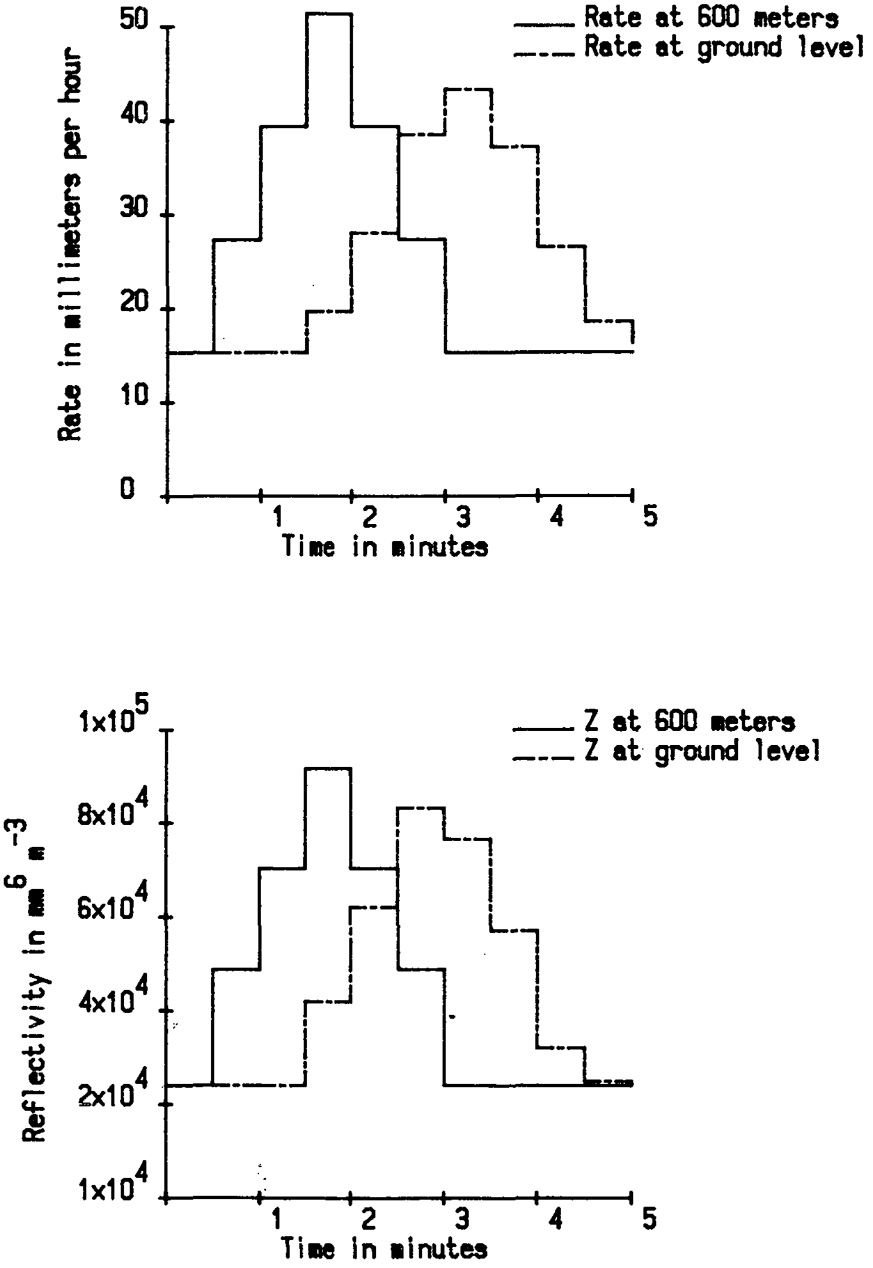

Figure 2. **The effects of differential drop velocity on rain rates and reflectivity.**

capabilities of storms are examined in a simple comparison of the two most relevant treatments. The significance of the difference between the seeded and unseeded (and unpenetrated) clouds for the mean echo top height (variable number 13), area (60), volume (28), mass (36), rainflux at 3° elevation angle (68), rainflux at 6 km (76) and precipitable water (84) are listed in Table 1 (Galpin, 1988; Appendix A, Table E). In this data stratification no cases are included without pretreatment echoes or with the coalescence time parameter less than 2.

This table looks promising for seeding effects with 23 significant cases at the 5% level. Obviously, however, further study is required to remove the effects of the pretreatment (-10 to 0) bias. This is being examined with a covariance analysis. Nevertheless, it appears that the requirement for the existence of pretreatment echo employed by the CSIR statisticians may be contributing to the difference with the earlier CloudQuest analysis. For example, this sample of 65 echoes only shows a factor of two rainflux (and echo area) enhancement for the seed group, compared with the factor of four increases for the total sample examined by CloudQuest in the 1986/87 Annual Report (N = 147 storms). The CloudQuest data included two categories not used in the CSIR analysis, (1) penetrated storms which were not seeded, and (2) storms with no pretreatment cell echo. The existence of pretreatment echo, makes it possible to examine one of the many possible bias indicators (the radar observations before seeding). Unfortunately, in the smaller 65 echo CSIR subsampler all but one of these seven echo variables is significantly different for the seeded case before treatment. This suggests a biased subsample. However, although the possibility of accidental bias in sampling is always going to be relatively high given the number of variables which must be controlled, the total sample does not appear to suffer bias. Furthermore, Gagin has also shown that early seeding (relative to echo life) may strongly impact on the effectiveness of the treatment. Thus, the early seeded PAWS cases must also receive more attention. These cases probably make a very substantial contribution to the overall PAWS seeding effect. Consequently, the pretreatment echo constraint will be relaxed for some future CSIR analyses.

The use of numerical cloud models is also suggested, both to eliminate the effects of bias and to better link cause to effect.

Cloud Models

In the past, a broad spectrum of numerical cloud modelling studies have been undertaken at CSIR. These related to cloud growth processes and precipitation development, and included the use of large computers. One, two and three-dimensional cloud models (Steiner, 1973) studied the energy and water transformations during the lives of storms (Reuter, 1988).

Table 1: Significance probabilities for seeding effects (mean comparison via re-randomization). Data stratification, coalescence active, and echo required before treatment, N = 65 (see Galpin, 1988; Appendix A, Table E.)

Period (min)	-10 to 0	0 to 10	10 to 20	20 to 30	30 to 40
Variable					
Height (13)	-	-	.95	.95	-
Volume (28)	.99	1.00	1.00	.99	.95
Mass (36)	.99	1.00	1.00	.99	.91
Area (60)	.94	1.00	.99	.99	.97
Rainflux at 3° (68)	.99	1.00	.99	.99	.98
Rainflux at 6 km (76)	.97	1.00	.99	.98	-
Precipitable water (84)	1.00	1.00	1.00	.99	-

However, more basic scientific studies have also been performed at CSIR. These related to the more realistic calculation of the collection kernel for cloud drop collisions in a turbulent environment via a stochastic model. The model assumes white noise random drop displacements proportional to the turbulent diffusion coefficient and introduced the use of stochastic differential equations into the field of precipitation studies. The Fokker- Plank type of differential equation needs to be solved numerically only once, yet covers the entire probabilistic nature of the problem. Thus, the new model avoids the high number of calculations required for the older Monte Carlo simulations. The results show that turbulence enhances the probability of collisions, particularly for droplet radii of less that 50 μm (Reuter *et al.*, 1988). However, the enhancement does not appear to be adequate to explain observations of the most rapid rain development rates.

Now, extensive application of simpler one-dimensional numerical cloud models will also be made to identify the atmospheric thermodynamic conditions suitable for successful cloud seeding.

In the future, it is planned to adopt the newer multi-dimensional cloud models which utilise Doppler radar observations as input to analyse the results of cloud seeding activities. These models are expected to be a powerful tool in identifying seeding signals amongst the otherwise great natural variability of convective rain processes since the rapidly updated radar input may supply very realistic pre-seeding in cloud conditions to the model predictions. Great reductions in experiment duration and in the uncertainty of establishing a seeding effect are possible. Most important, the actual physical mechanisms acting will be better identified.

REFERENCES

DIXON M J and MATHER G K, 1986: Radar evaluation of a randomized rain augmentation experiment - Some preliminary results. *Preprints: 10th Conference on Weather Modification*, AMS, Boston, 139-141.

GALPIN J S, 1988: Preliminary analysis of radar data concerning the Nelspruit cloud seeding experiment. CSIR/CACDS CKOMP 88/7. 27pp + Appendices A-E.

GROSH R C, 1988a: The science of rainmaking - An historical perspective. *Newsletter, SA Society for Atmos. Sci.*, 8, 2-10.

GROSH R C, 1988b: Editor, 1987/88 PAWS report. CSIR/EMA C-88107, 200pp.

GROSH R C, 1989: Rainmaking - The promise for South Africa. *Proceedings First Biennial Conference*, Water Inst. South Africa, Parkhurst, 12pp.

KYLE T G, 1975: The measurement of water content by an evaporator. *J. Appl. Meteor.*, 14, 327-332.

MATHER G K, MORRISON B J and MORGAN G M, 1986: A preliminary assessment of the importance of coalescence in convective clouds of the Eastern Transvaal. *J. Clim. Appl. Meteor.*, 25, 1780-1784.

MORGAN G M, 1986: Accepted: *Theoretical and Applied Climatology*, Springer Verlag, Vienna.

MORRISON B J, MATHER, G K and MORGAN G M, 1986: Aircraft observations of target turrets on multicellular storms showing radar response to dry-ice seeding. *Preprints: 10th Conference on Weather Modification*, AMS, Boston, 204-209.

REUTER G W, DE VILLIERS R and YAVIN Y, 1988: *J. Atmos. Sci.*, **45**(5), 765-773.

REUTER G W, 1988: *Beitr. Phys. Atmosph.*, 61, 30-38.

STEINER J T, 1973: *J. Atmos. Sci.*, 30, 414-435.