PROGRAMME
FOR
ATMOSPHERIC WATER SUPPLY
(PAWS)

PHASE 2
1987 to 1989
FINAL REPORT

VOLUME 1
EXECUTIVE SUMMARY

Report to the
Water Research Commission
Pretoria, South Africa

by

CSIR
and
CloudQuest (Pty) Ltd

March 1990

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VOLUME I

Executive Summary

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ABSTRACT

The objective of the Programme for Atmospheric Water Supply (PAWS) was to evaluate the potential for increasing the summertime convective rainfall of the Eastern Transvaal. This report describes the findings of the second phase of PAWS, 1987-1989.

PAWS 2 confirmed the main statistical findings of earlier PAWS research on the treatment of isolated multicellular convective storms with dry ice. A significant increase in rainfall was indicated for the period 30 to 40 minutes after treatment. Although some inadvertent bias was present, after its removal the increase during this period was about 50%. Much attention was also devoted to refining rain and cloud microphysics measurement techniques. The analysis of morning soundings suggested that dynamic seeding effects should be infrequent in the Eastern Transvaal since significant induced vertical cloud growth was indicated on about 10% of all convective season days. However, when present, vertical growth should be strong. Furthermore, cloud models and liquid water observations both indicated strong glaciogenic seeding possibilities. Sounding analysis suggested that up to 25% of the days may have natural cloud top heights between -10°C and -20°C.

PAWS 2 marks the final PAWS research. To avoid duplication of resources in this increasingly expensive research, the effort has been consolidated with the Programme for Precipitation Research in South Africa led by the Weather Bureau.

PREFACE

The Programme for Atmospheric Water Supply (PAWS) was a research project to determine the potential for rain enhancement by the treatment of summertime convective clouds.

This report describes the very important results from the last three years, or Phase 2, of PAWS. These results support a favourable, but qualified, verdict for rain stimulation in the Eastern Transvaal.

Volume 1 is a summary of the conclusions reached by PAWS.

Volumes 2 and 3 provide details on the field work and analyses behind the conclusions.

The staff of each of the responsible organizations who performed this work is listed in Appendix A of this volume.

Appendix B lists the publications which have already been generated under this programme and provides a list of those manuscripts submitted for publication.

Appendix C acknowledges those individuals who served on the Steering Committee and guided this work over the past three years.

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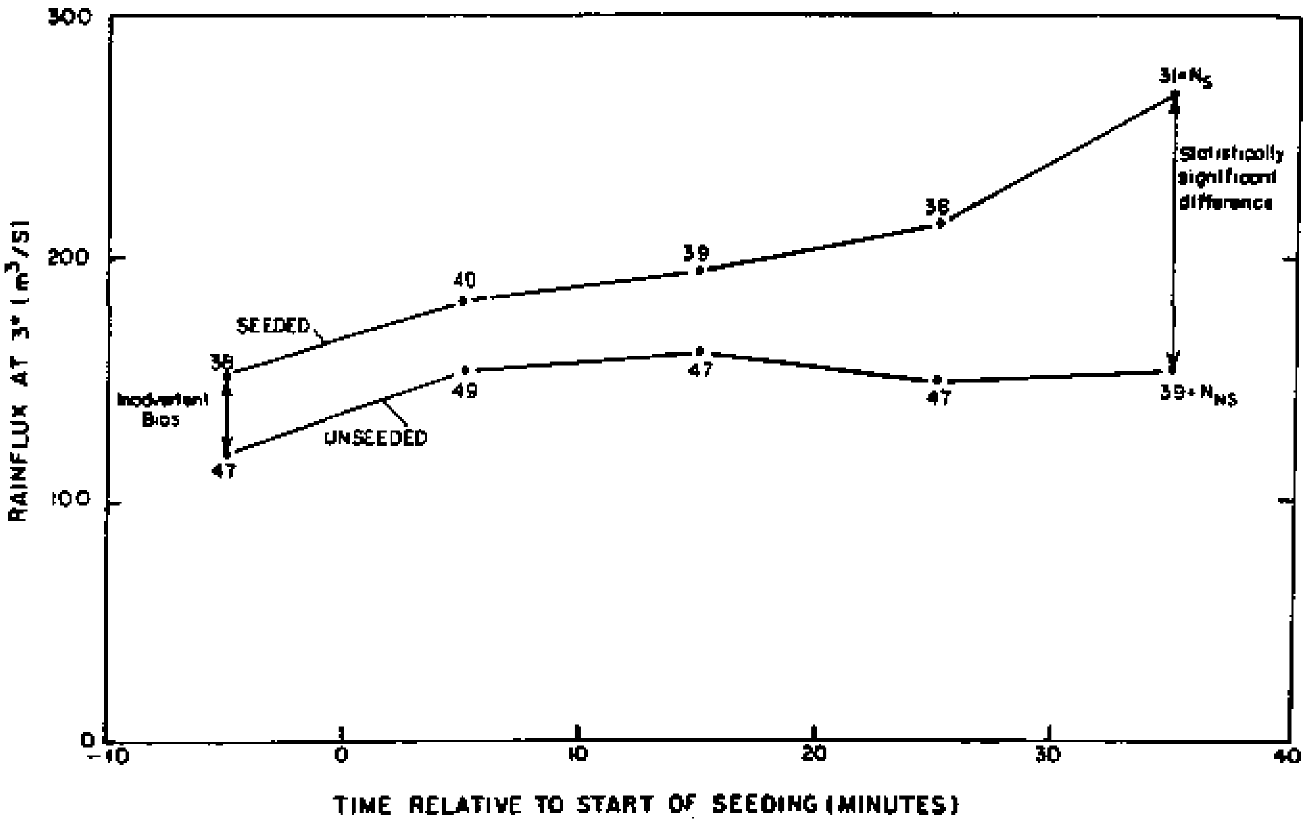
1.0 RESEARCH SUMMARY

The Programme for Atmospheric Water Supplies (PAWS) is sponsored by the Water Research Commission to determine the potential for augmenting the country's marginal water supplies by artificial rain stimulation. PAWS II, the second three-year phase of the programme had many important research achievements. The period was also marked by the participation of CSIR in PAWS research as the scientific directorate of the project. CSIR contributed to the statistical and physical analyses of the PAWS data, as well as to the development of PAWS rain measurement technology for ground radars, electrical observations of storms and several types of numerical cloud model analyses. Information exchanges between CSIR and CloudQuest, the Nelspruit Company contracted for field operations, have lead to an improved project and more clearly defined and thoroughly discussed results. In addition, interaction with the independent Bethlehem Precipitation Research Project was greatly increased during PAWS II. The PAWS radar was also moved to Carolina, the hydrologic centroid of the Eastern Transvaal and the most promising location for implementing a successful rain stimulation technology. However, the main accomplishment was the collection and analysis of the third season of experimental cloud seeding data, and the commencement of a new experiment with the radar at the Carolina site.

1. Apparent seeding effects on radar measured rainfall are observed on average primarily in the period 20 to 40 minutes after seeding (Figure 1). In the 30 to 40 minute window, the rainfall increase is statistically significant and appears to be on the order of 50% after a crude bias adjustment is made. The increase follows a physically logical chain of events beginning with an increase in the height of the centre of gravity of seeded storms in the 0 to 10 minute period after seeding. In the following 10 minutes the seeding change persists in the form of increased reflectivities aloft which descend during the 20 to 30 minute window. The observed chain strongly suggests that artificial glaciation is occurring and causing precipitation to grow more reflective (larger) as it rises in the seeded

FIGURE 1: SEEDING EFFECT ON RAINFLUX (N_S, N_{NS}, NUMBER OF SEEDED AND UNSEEDED STORMS)



updraught. As the updraught weakens, the enhanced rain volume descends and the storm area also expands. The area expansion accounts for about half the percentage increase in rain flux. Thus, the seeded storms are both larger and more intense. Both enhancements could be the result of either "dynamic" or "static" seeding effects (1,2).

Areas of concern for this finding relate to sample size. There are on the order of 40 cases in the seed and no seed groups (3). While this is large relative to other similar experiments, more cases are desirable, especially in the later stages of cloud development.

Other areas of major accomplishment during the past three years are in the development and application of airborne cloud physics instrumentation, numerical cloud models, and rain measurement via ground radar and rain gauges:

2. Specialised cloud physics instrumentation suitable for the very wet Eastern Transvaal clouds was developed at Nelspruit. This includes a unique total water meter, in which the Learjet engine evaporates the contents of a much larger sample of air than other similar instruments sample (5). The total water content is determined by Lyman-alpha attenuation. Another important system, combining measurements from two other commercially available instruments (a laser probe and a radar) was developed to determine cloud particle density and phase (2). Other Learjet instrumentation for high speed conditions provides the ability to distinguish small water drops from ice crystals. Thus, key aspects of the natural precipitation formation mechanisms can be identified. These findings favour application of seeding techniques intended to increase the efficiency of the natural rainfall process. However, large natural supercooled drops at the -10°C level are also found in warm based PAWS clouds when there is sufficient buoyancy and a local accumulation zone (a strong updraught supporting high liquid water contents) has been documented (2).

Several local cases of aircraft-produced ice crystals were detected by the PAWS Learjet (2). These plumes of high concentrations of uniformly sized ice crystals, similar to the seeding plume caused by dry ice, could have ramifications in terms of future experimental designs, since there is a suggestion from the analysis of the seeding experiment that APIPS may be contaminating the no seed data set.

The cloud base aircraft was also equipped with a 2D-P probe and a radar. The 2D-P probe measures the concentration and size distribution of rain drops. Together with the crude airborne measurements of vertical air motion, this system can produce estimates of rain rates along the track of the aircraft.

3. Sounding analysis via numerical cloud models has shown that dynamic seeding effects are not likely to be frequent during the morning in the Eastern Transvaal (6). Only about 10% of the morning soundings examined had model predicted vertical cloud growth for the seeding simulation above the natural simulation by more than 1 km. Although when dynamic growth potential was present it was often great, it appears that the eastern Transvaal has a very low frequency of opportunities for dynamic seeding alterations of cloud growth processes compared with other locations. Nevertheless, these days add up to about half the *number* of actual seeding opportunities. Furthermore, about one quarter of the soundings had natural cloud heights predicted between -10 to -20°C, where natural glaciation is unlikely to be strong but artificial glaciation may be effective. Thus, these cases are thought to be susceptible to glaciogenic seeding effects in general. In addition, a smaller nonsynchronous data set is available for "afternoon" soundings. This data is being examined now.

Another important PAWS finding is derived from observations of cloud drops at the most common cloud penetration levels (-10°C) in clouds around the Nelspruit experimental area (2).

The ratio of cloud base temperature to a measure of cloud buoyancy at 500 mb (dubbed the coalescence time parameter, or CTP) has been found very useful in separating those clouds with ice from those containing water drops at 10°C. It was found that when the seeding experiment was stratified using the CTP, much stronger results were obtained when comparing only those storms growing in an environment in which the CTP was greater than 2.

Numerical modelling studies were also undertaken to examine (a) the turbulent collision process that is important to rain drop growth, (b) the source of downdraught air, and (c) the water budget of convective storms (9). The principal results indicate that downdraught air comes mainly from the cloud boundary and near its base (although a small fraction may have come from near cloud top as well), that in spite of significant evaporative cooling non-hydrostatic pressure gradients contribute equally to downdraught initiation, and that downdraughts are most likely to form on the cool (diluted) downshear side of a cloud. Although model studies indicated that there was little difference in downdraught speeds between liquid and mixed phase clouds, the early air current findings show the possibilities that cloud models have for dealing with key cause and effect issues related to natural and artificially stimulated cloud growth and propagation. Since the seeding level air appears to have little impact on downdraught air in local clouds, future model and observational studies of the impact of artificially stimulated updraughts on surface pressure and convergence have the highest priority.

4. A variety of radar rain measurement studies have shown the need to consider the effects of winds aloft, terminal fall speeds, and the highly non-linear aspects of the Z-R relationship on radar rain estimates (10,11). Furthermore, the global mean Z-R relationships for convective and thunderstorm rainfall (and their variability) have been identified (Table 1).

Table 1. Global Z-R Relationships (12) for:

Mixed Convective Storms	$Z = 260\ R^{1.43}$
Thunderstorms	$Z = 385\ R^{1.46}$

These provide the best first guess radar calibration when rain gauge information is not available. A survey (13) has shown that simple gauge calibration can produce radar rain measurements of storms which are accurate to within about $\pm 25\%$ on average (with a $\pm 20\%$ rms error). It follows that simple gauge calibration of radars limits their use to detecting seeding signatures that are above ~25%. A feasibility study has shown that a uniform rain network with a gauge density of about 100 km^2/gauge, such as was used in the American FACE project, is probably adequate for more complicated radar calibration as it provides a high probability of detection for the typical small (area ~200 km^2) multiple cellular storms that have been studied in the experiments to date. A new radar with a narrow beam width would increase the useful range of the observations and thus increase the number of storms sampled per year and thereby decrease future experimental duration. Also it would be best for a new radar to employ a 10 cm wavelength to avoid attenuation.

A workshop was held at Berg-en-Dal in the Kruger National Park in August 1989 to determine the best future course of South African rain stimulation research. Four special foreign consultants, as well as local scientists, advisors and administrators involved in the project participated at the workshop. The foreign advisors made several important recommendations. As expected, the multiple Doppler radar network was identified as a primary research tool to determine the critical air flow structure, water budgets and seeding trajectories for typical storms in future South African rain stimulation projects. Radar studies of storm mergers and growth patterns were also highly recommended, as were airborne studies of the closely related problem of determining cloud base air current structure. Advanced numerical cloud models have also been established as being required tools for identifying cause and effect relationships in future SA rain stimulation projects.

2.0 REFERENCES

(1) Grosh R C, Hodson M, Muller C, Hofmeister G, Reuter G W and Galpin J S, 1989: Programme for Atmospheric Water Supply, Phase 2, 1987-1989. CSIR Annual Report 1989, November 1989, Water Research Commission, Pretoria, pp160.

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(3) Galpin J S, 199. Overview of the statistical analyses of the radar data from the Nelspruit cloud seeding experiments, in (1), p125-160.

(4) Grosh R C and Muller C, 1989. PAWS case studies, in (1), 99-124.

(5) Morgan G M Jr, Morrison B J and Mather G K, 1989. Measurement of total and condensed water mixing ratios in warm based cumulus clouds by a jet engine evaporation technique. To be published in Theoretical and Applied Climatology, Springer and Verlag, Vienna.

(6) Grosh R C and Hofmeister G, 1989. Sounding analysis, in (1), 73-87.

(7) Grosh R C, 1989. A note on the coalescence time parameter, in (1), 88-98.

(8) 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., 25-22, 1780-84.

(9) Reuter G, 1989. Review of earlier PAWS cloud modelling, in (1), 64-72.

(10) Hodson M, 1989. Radar rain measurement, fall speed and wind effects, in (1), 2-15.

(11) Grosh R C, 1989. The highly non-linear aspects of Z-R and VT-Z caused by rain drop terminal fall speeds, in (1), 16-21.

(12) Grosh R C, 1988. 1987/88 PAWS report. Water Research Commission, Pretoria, 1-7.

(13) Grosh R C, 1989. A review of raindrop size distribution measurements, in (1), 28-41.

(14) Grosh R C, 1989. Rain sampling feasibility study, in (1), 48-63.

APPENDIX A

PAWS PERSONNEL

<u>CSIR</u>

EMATEK:

Ronald C Grosh, Scientific Director
Griffith M Morgan, Former Scientific Director

Gerhard Reuter, Cloud Modeller
Christine Muller, Meteorologist
Gisela Hofmeister, Cloud Modeller
M Hodson, Scientist
Dr D Proctor, Scientist

DATATEK:

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Irma Auret, Statistician
M B Mare, Statistician

<u>CLOUDQUEST (PTY) LTD</u>

Graeme K Mather, Operations Director

Erika Botha, Electronics Engineer
Maureen Dreyer, Secretary
Peter McNaught, Technician
Ian Ross, Technician
Rob Parsons, Programmer/Pilot
Fritz van der Westhuizen, Chief Pilot
V Wightman, Programmer/Pilot
Ken Young, Electrical Engineer

APPENDIX B

PAWS PUBLICATIONS

CONFERENCE PROCEEDINGS AND PRESENTATIONS

Galpin J S, 1988. Some statistical aspects of the analysis of the radar data from the Nelspruit weather modification experiment. Paper presented at the Annual Conference of the SA Statistical Association, Pretoria.

Galpin J S and Auret I, 1988. Some statistical aspects of the radar data from the Nelspruit Weather modification experiment. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria.

Grosh R C, 1988. The variability of Z-R relationships. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria

Grosh R C, 1989. Rain making - The promise for South Africa. Paper presented at the 1st Biennial Conference and Exhibition, Water Institute of South Africa, Cape Town. 29 March.

Grosh R C, 1989. The highly non-linear aspect of Z-R and VT-Z cased raindrop fall speeds. Paper presented at the 24th Conference on radar Meteorology, American Meteorol. Society, Boston. (Preprint Vol. 49-54).

Grosh R C, 1989. Z-R relationships and radar rainfall measurement. Paper presented at the 6th Annual Conference of the SA Society for Atmospheric Sciences, Pretoria. 26-27 October.

Grosh R C, 1989. Radar observations of heavy thunderstorms. Paper presented at the 4th South African National hydrological Symposium, Pretoria. 20-22 November.

Hodson M C, 1988. Comparison of vertically pointing radar and rain gauge rainfall measurements. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria.

Mather G K, 1987. Operations or research? Towards an effective compromise. Paper presented at the First International Meeting on Agriculture and Weather Modification, Leon, Spain. January.

Mather G K, 1988. An analysis of the 3-year PAWS exploratory seeding experiment. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria.

Mather G K, 1988. Estimates of precipitation embryo densities using measurements from an aircraft radar. Seminar, SAWB, Pretoria. May.

Mather G K, 1989. A new cloud seeding hypothesis? Paper presented at the 6th Annual Conference of the SA Society for Atmospheric Sciences, Pretoria. 26-27 October.

Mather G K, 1989. Towards the development of a usable cloud seeding technology. Paper presented at the 8th seminar of the DR de Wet Forestry Research Centre Seminar Series, Sabie. 2 November.

Morgan G M, Morrison B J and Mather G K, 1987. Measurement of total and condensed water mixing ratio in warm-based cumulus clouds. Paper presented at the Second International Conference on Hail Prevention, Ljubljana, Yugoslavia. October.

Muller C M and Grosh R C, 1989. A PAWS case study. Paper presented at the 6th Annual Conference of the SA Society for Atmospheric Sciences, Pretoria. 26-27 October.

Roos D vdS, 1988. The PAWS project. Seminar, Steirische Hagel Abwehrgenossenschaft, Graz, Austria. 1 September.

PUBLISHED PAPERS

Grosh R C, 1988. Milking the clouds. CSIR Scientiae, 29 (2), 14-18.

Grosh R C, 1988. The science of rainmaking - An historical perspective. S A Society of Atmospheric Sciences Newsletter, 8, 2-10

Grosh R C, Muller C M, Galpin J, Auret I, Hodson M C, Proctor D E, Reuter G and Roos D vdS, 1989. PAWS reconstructed. J. Weather Modification, Weather Modification Ass., Fresno, 94-99.

Mather G K, 1988. Comments on "microphysical" and radar observations of seeded and non-seeded continental cumulus clouds. Journal of Climate and Applied Meteorology, 27, 1193.

Mather G K, 1989. Estimates of precipitation embryo densities using measurements from an aircraft radar. J. Applied Meteorology, 28, 1089-1097.

Morgan G M, Morrison B J and Mather G K, 1989. Measurement of total and condensed water mixing ratios and warm based cumulus clouds by a jet engine evaporation technique. Theoretical and Applied Climatology, 40, Springer-Verlag, 187-199.

Reuter G W, 1987. Penetrative downdraughts in mixed-phase clouds - a numerical study. SA Journal of Physics, 10, 139-145.

Reuter G W and Yau M K, 1987. Mixing mechanisms in cumulus congestus clouds. Part 1: Observations. Journal of the Atmos. Sci., 44, 781-797.

Reuter G W and Yau M K, 1987. Mixing mechanisms in cumulus congestus clouds. Part 2: Numerical simulations. Journal of the Atmos. Sci., 44, 798-827.

Reuter G W and Yau M K, 1987. Numerical modelling of cloud development on a sheared environment. Atmospheric Physics, 60, 65-80.

MANUSCRIPTS SUBMITTED OR UNDER PREPARATION

Grosh R C, 1990. The highly non-linear aspects of Z-R and VT-Z caused by raindrop fall speeds. (J. Clim. Appl. Meteor.)

Grosh R C and Galpin J, 1990. African rain stimulation experiments. (J. Clim. Appl. Meteor.)

APPENDIX C

PAWS STEERING COMMITTEE

The Programme for Atmospheric Water Supply (PAWS) was financed by the Water Research Commission.

The Steering Committee responsible for the second phase of PAWS (1987-1989) was the following:

Chairman :	Dr P J T Roberts (1987)	Water Research Commission
	Dr G Green	Water Research Commission
Secretary:	F P Marais	Water Research Commission

Members (as on 12 December 1989):

H Maaren	Water Research Commission
Dr D vdS Roos	EMATEK, CSIR
Mr H Best	Dept of Water Affairs
Dr A Seed (Alt)	Dept of Water Affairs
Dr N J Geyer	Transvaal Agricultural Union
Mr G Groenewald	Dept of Environment Affairs
Dr R Bruintjes (Alt)	Dept of Environment Affairs
Mr J C L van Schalkwyk	Lowveld Regional Services Council
Dr J R Eloff	Dept of Agricultural Development

Other individuals and organisations in the Lowveld and elsewhere who supported this research are thanked for their various contributions.

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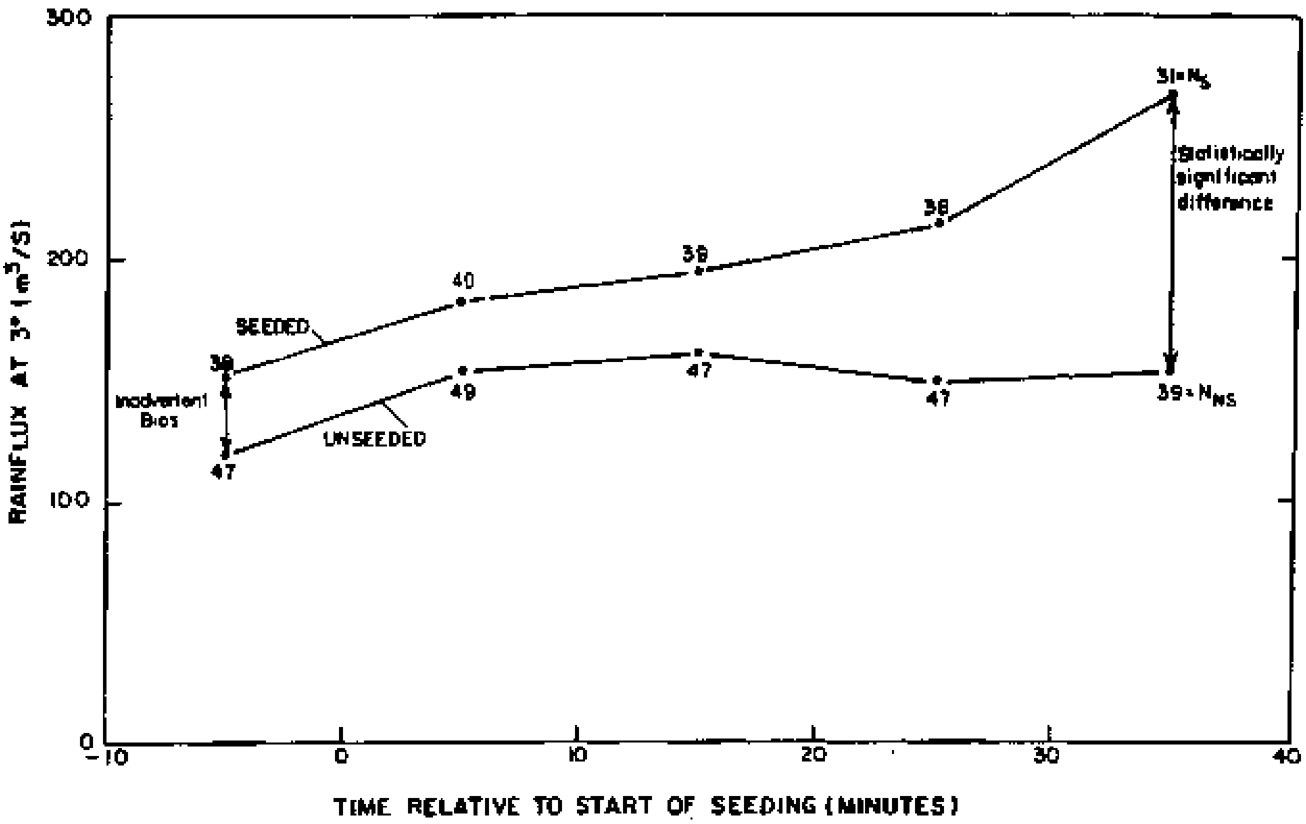

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(3) Galpin J S, 199. Overview of the statistical analyses of the radar data from the Nelspruit cloud seeding experiments, in (1), p125-160.

(4) Grosh R C and Muller C, 1989. PAWS case studies, in (1), 99-124.

(5) Morgan G M Jr, Morrison B J and Mather G K, 1989. Measurement of total and condensed water mixing ratios in warm based cumulus clouds by a jet engine evaporation technique. To be published in Theoretical and Applied Climatology, Springer and Verlag, Vienna.

(6) Grosh R C and Hofmeister G, 1989. Sounding analysis, in (1), 73-87.

(7) Grosh R C, 1989. A note on the coalescence time parameter, in (1), 88-98.

(8) 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., 25-22, 1780-84.

(9) Reuter G, 1989. Review of earlier PAWS cloud modelling, in (1), 64-72.

(10) Hodson M, 1989. Radar rain measurement, fall speed and wind effects, in (1), 2-15.

(11) Grosh R C, 1989. The highly non-linear aspects of Z-R and VT-Z caused by rain drop terminal fall speeds, in (1), 16-21.

(12) Grosh R C, 1988. 1987/88 PAWS report. Water Research Commission, Pretoria, 1-7.

(13) Grosh R C, 1989. A review of raindrop size distribution measurements, in (1), 28-41.

(14) Grosh R C, 1989. Rain sampling feasibility study, in (1), 48-63.

APPENDIX A

PAWS PERSONNEL

<u>CSIR</u>

EMATEK:

Ronald C Grosh, Scientific Director
Griffith M Morgan, Former Scientific Director

Gerhard Reuter, Cloud Modeller
Christine Muller, Meteorologist
Gisela Hofmeister, Cloud Modeller
M Hodson, Scientist
Dr D Proctor, Scientist

DATATEK:

Dr J Galpin, Chief Statistician
Irma Auret, Statistician
M B Mare, Statistician

<u>CLOUDQUEST (PTY) LTD</u>

Graeme K Mather, Operations Director

Erika Botha, Electronics Engineer
Maureen Dreyer, Secretary
Peter McNaught, Technician
Ian Ross, Technician
Rob Parsons, Programmer/Pilot
Fritz van der Westhuizen, Chief Pilot
V Wightman, Programmer/Pilot
Ken Young, Electrical Engineer

APPENDIX B

PAWS PUBLICATIONS

CONFERENCE PROCEEDINGS AND PRESENTATIONS

Galpin J S, 1988. Some statistical aspects of the analysis of the radar data from the Nelspruit weather modification experiment. Paper presented at the Annual Conference of the SA Statistical Association, Pretoria.

Galpin J S and Auret I, 1988. Some statistical aspects of the radar data from the Nelspruit Weather modification experiment. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria.

Grosh R C, 1988. The variability of Z-R relationships. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria

Grosh R C, 1989. Rain making - The promise for South Africa. Paper presented at the 1st Biennial Conference and Exhibition, Water Institute of South Africa, Cape Town. 29 March.

Grosh R C, 1989. The highly non-linear aspect of Z-R and VT-Z cased raindrop fall speeds. Paper presented at the 24th Conference on radar Meteorology, American Meteorol. Society, Boston. (Preprint Vol. 49-54).

Grosh R C, 1989. Z-R relationships and radar rainfall measurement. Paper presented at the 6th Annual Conference of the SA Society for Atmospheric Sciences, Pretoria. 26-27 October.

Grosh R C, 1989. Radar observations of heavy thunderstorms. Paper presented at the 4th South African National hydrological Symposium, Pretoria. 20-22 November.

Hodson M C, 1988. Comparison of vertically pointing radar and rain gauge rainfall measurements. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria.

Mather G K, 1987. Operations or research? Towards an effective compromise. Paper presented at the First International Meeting on Agriculture and Weather Modification, Leon, Spain. January.

Mather G K, 1988. An analysis of the 3-year PAWS exploratory seeding experiment. Paper presented at the 5th Conference of the SA Society for Atmospheric Sciences, Pretoria.

Mather G K, 1988. Estimates of precipitation embryo densities using measurements from an aircraft radar. Seminar, SAWB, Pretoria. May.

Mather G K, 1989. A new cloud seeding hypothesis? Paper presented at the 6th Annual Conference of the SA Society for Atmospheric Sciences, Pretoria. 26-27 October.

Mather G K, 1989. Towards the development of a usable cloud seeding technology. Paper presented at the 8th seminar of the DR de Wet Forestry Research Centre Seminar Series, Sabie. 2 November.

Morgan G M, Morrison B J and Mather G K, 1987. Measurement of total and condensed water mixing ratio in warm-based cumulus clouds. Paper presented at the Second International Conference on Hail Prevention, Ljubljana, Yugoslavia. October.

Muller C M and Grosh R C, 1989. A PAWS case study. Paper presented at the 6th Annual Conference of the SA Society for Atmospheric Sciences, Pretoria. 26-27 October.

Roos D vdS, 1988. The PAWS project. Seminar, Steirische Hagel Abwehrgenossenschaft, Graz, Austria. 1 September.

PUBLISHED PAPERS

Grosh R C, 1988. Milking the clouds. CSIR Scientiae, 29 (2), 14-18.

Grosh R C, 1988. The science of rainmaking - An historical perspective. S A Society of Atmospheric Sciences Newsletter, 8, 2-10

Grosh R C, Muller C M, Galpin J, Auret I, Hodson M C, Proctor D E, Reuter G and Roos D vdS, 1989. PAWS reconstructed. J. Weather Modification, Weather Modification Ass., Fresno, 94-99.

Mather G K, 1988. Comments on "microphysical" and radar observations of seeded and non-seeded continental cumulus clouds. Journal of Climate and Applied Meteorology, 27, 1193.

Mather G K, 1989. Estimates of precipitation embryo densities using measurements from an aircraft radar. J. Applied Meteorology, 28, 1089-1097.

Morgan G M, Morrison B J and Mather G K, 1989. Measurement of total and condensed water mixing ratios and warm based cumulus clouds by a jet engine evaporation technique. Theoretical and Applied Climatology, 40, Springer-Verlag, 187-199.

Reuter G W, 1987. Penetrative downdraughts in mixed-phase clouds - a numerical study. SA Journal of Physics, 10, 139-145.

Reuter G W and Yau M K, 1987. Mixing mechanisms in cumulus congestus clouds. Part 1: Observations. Journal of the Atmos. Sci., 44, 781-797.

Reuter G W and Yau M K, 1987. Mixing mechanisms in cumulus congestus clouds. Part 2: Numerical simulations. Journal of the Atmos. Sci., 44, 798-827.

Reuter G W and Yau M K, 1987. Numerical modelling of cloud development on a sheared environment. Atmospheric Physics, 60, 65-80.

MANUSCRIPTS SUBMITTED OR UNDER PREPARATION

Grosh R C, 1990. The highly non-linear aspects of Z-R and VT-Z caused by raindrop fall speeds. (J. Clim. Appl. Meteor.)

Grosh R C and Galpin J, 1990. African rain stimulation experiments. (J. Clim. Appl. Meteor.)

APPENDIX C

PAWS STEERING COMMITTEE

The Programme for Atmospheric Water Supply (PAWS) was financed by the Water Research Commission.

The Steering Committee responsible for the second phase of PAWS (1987-1989) was the following:

Chairman :	Dr P J T Roberts (1987)	Water Research Commission
	Dr G Green	Water Research Commission
Secretary:	F P Marais	Water Research Commission

Members (as on 12 December 1989):

H Maaren	Water Research Commission
Dr D vdS Roos	EMATEK, CSIR
Mr H Best	Dept of Water Affairs
Dr A Seed (Alt)	Dept of Water Affairs
Dr N J Geyer	Transvaal Agricultural Union
Mr G Groenewald	Dept of Environment Affairs
Dr R Bruintjes (Alt)	Dept of Environment Affairs
Mr J C L van Schalkwyk	Lowveld Regional Services Council
Dr J R Eloff	Dept of Agricultural Development

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APPENDIX D

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