The South African rainfall enhancement programme: 1997-2001

Deon E Terblanche*, Marion P Mittermaier#, Roelof P Burger, Karel JP de Waal and Xolile G Ncipha
South African Weather Service, Private Bag X15, Bethlehem 9700, South Africa

Abstract

This paper provides a summary of the South African Rainfall Enhancement Programme (SAREP) that was conducted in the Limpopo Province of South Africa. SAREP included an operational cloud-seeding campaign based on the South African developed hygroscopic flare-seeding technology which ran from December 1997 to the end of December 2000. In addition, a radar-based storm climatology was compiled using data collected during the period October 2000 to April 2001. During the cloud-seeding campaign 95 storms were seeded of which 37 were selected for treatment early in their lifetimes. This subset allowed a 'time of origin' analysis to quantify the seeding effect on radar-estimated rainfall. The Thunderstorm Identification Tracking Analyses and Nowcasting (TITAN) software was upgraded as part of SAREP for such an analysis. It was found that seeded storms on average produced twice the radar-determined rainfall that their controls produced. The cost for the additional rainfall was determined to be about R0.04/m^3.

The radar-based storm climatology for the 10 000km^2 target area was compiled using storm lifetime of 15 min and 30 dBZ radar reflectivity as the TITAN storm-tracking thresholds. It was found that more than 2 000 of these radar storm tracks affected the target area during the 7 months from October 2000 to April 2001. By comparing these radar storm tracks with those that were seeded, it was possible to identify the 290 radar storm tracks that could have been regarded as legitimate candidates for seeding. Based on the preliminary findings of this study, it is suggested that if 75 of the legitimate candidate storms in the specific target area are seeded, a marked (~10%) increase in area rainfall over the target area could be realised. This would have considerable socio-economic benefits. It is recommended that further development of this technology should remain a high priority in an integrated water resource management plan for South Africa.

Keywords: rainfall enhancement, cloud seeding, storm climatology

Introduction

The development of the hygroscopic flare-seeding technology

The South African Rainfall Enhancement Programme (SAREP) was a semi-operational cloud-seeding project that was conducted in the Limpopo Province between 1997 and 2001. It was based on the hygroscopic flare-seeding technology that was developed in South Africa by the National Precipitation Research Programme (NPRP) during the period 1990 to 1997.

The NPRP came about when the previously separate projects at Bethlehem (the Bethlehem Precipitation Research Project) and at Nelspruit/Carolina (the Programme for the Augmentation of Atmospheric Water Supply) amalgamated in 1990. This national programme was jointly funded by the South African Weather Bureau (now the South African Weather Service – SAWS) and the Water Research Commission (WRC). Co-operation under the banner of the NPRP led to significant progress in rainfall enhancement techniques in South Africa as well as in the development of the technologies to support such experiments. An internationally recognised highlight of the NPRP was the development of the hygroscopic seeding flare and its application to convective clouds. This flare is used for seeding growing convective clouds in the updraft areas below cloud base. Small (~0.5 μ) hygroscopic particles that act as efficient cloud condensation nuclei (CCN) are released when the flare burns. These particles alter the initial cloud droplet size distribution towards a broader spectrum with a lower droplet concentration. The modified distribution is conducive to inter-droplet collisions and the eventual growth of cloud droplets to rainfall through a process known as coalescence. Coalescence is a very efficient precipitation formation process that is generally not active in the continental convective clouds over the interior of South Africa.

The initial tests conducted under the NPRP focused on characterising the physical and chemical properties of the burning flare and on conducting some seeding trials. Mather and Terblanche (1993a; b) reported the results of the initial tests to the WRC and in the local scientific literature. They presented arguments why this new approach to cloud seeding could be more appropriate to improve the rainfall production efficiency of local convective storms. In the following year, with a randomised seeding experiment well underway, Mather and Terblanche (1994) reported progress and some preliminary results to the international scientific community at a conference arranged by the World Meteorological Organisation (WMO), an agency of the United Nations. The findings were well received and the WMO declared that the South African work represented a significant step forward in the quest to develop viable methods to enhance rainfall. With the randomised experiment completed, Mather et al. (1997a; b) concluded their detailed reporting on the programme to the WRC and the international scientific community. In total 127 storms were selected as part of the randomised seeding experiment of which 62 were seeded and 65 were studied as controls. It was found that the seeded group provided statistically significant more rainfall than the control group.

For a short period after 1995 the NPRP was tasked to conduct semi-operational seeding around Tzaneen in the Limpopo Province. This project was carried out on request of the Limpopo Province government who also provided additional financial support. The NPRP used this opportunity to develop methods for the evaluation of non-randomised cloud seeding and intro-

Present affiliation: Met Office, FitzRoy Road, Exeter, EX1 3PB, UK
* To whom all correspondence should be addressed.
☎ +2758 303-5571; fax: +2758 303-2352;
e-mail: deon@weathersa.co.za
Received 19 September 2004; accepted in revised form 6 May 2005.

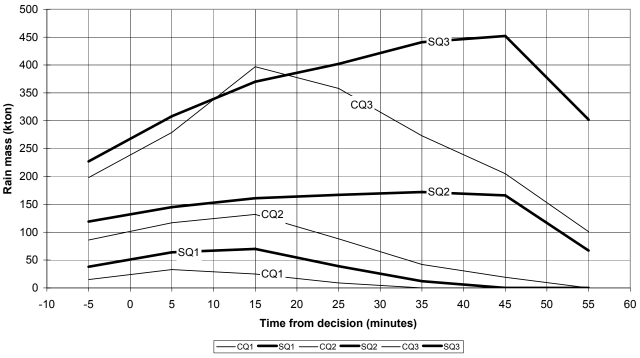


Figure 1a
The quartile analysis of the NPRP randomised seeding experiment. Thick lines represent the seeded group for each quartile (e.g. SQ1, SQ2 and SQ3) and thin lines the control group quartiles (e.g. CQ1, CQ2 and CQ3).

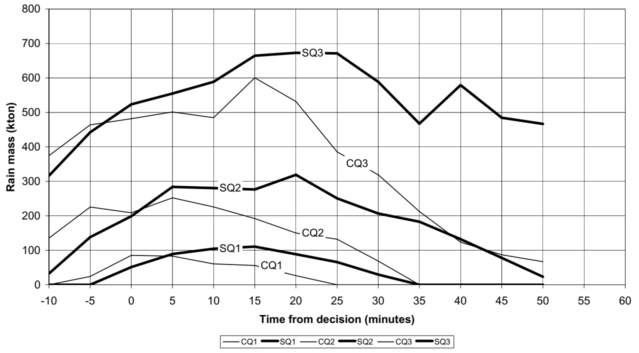


Figure 1b
As in Fig. 1a, but the quartile analysis of the Mexican randomised seeding experiment

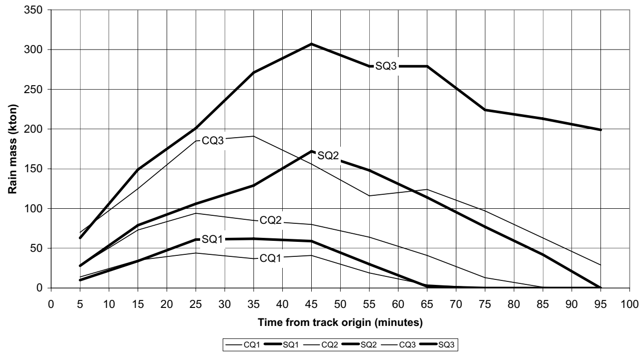


Figure 1c
As in Fig. 1a, but the quartile analysis of the NPRP semi-operational seeding experiment

duced new concepts to analyse radar data for this purpose (Terblanche et al., 2000). During the course of this project 60 storms were seeded and 60 storms with similar initial properties were selected as controls. Techniques developed in this project formed the basis for the consequent analysis performed in SAREP and which will be reported in this document. The main difference between the two analyses was that the Thunderstorm Identification, Tracking, Analyses and Nowcasting (TITAN) software developed by Dixon and Wiener (1993) at the National Centre for Atmospheric Research (NCAR) in the USA was adapted for an automated analysis of the SAREP data.

In April 1997, at the height of progress and success, the NPRP came to an abrupt end when national priorities resulted in the WRC having to refocus its funding allocations. SAWS could not carry the financial responsibility of the NPRP alone and the situation resulted in considerable uncertainty regarding the future of the South African research effort. A new proposal for the South African Rainfall Enhancement Programme (SAREP) was drafted and submitted in the second half of 1997, soon after Dr. Mather passed away. Funding for this new programme, with more emphasis on operations, became available towards the end of 1997. The Department of Water Affairs and Forestry, the Department of Agriculture and SAWS were now providing the funding. However, the funding base for SAREP proved to be rather unstable and this affected the way in which the field programmes were run. The Department of Arts, Culture, Science and Technology provided financial support during the last two seasons of SAREP after the Department of Agriculture withdrew its support.

After the demise of the NPRP, the international interest in the South African developments continued. Both Bigg (1997) and Silverman (2000) presented independent re-evaluations of the South African randomised experiment results in which they confirmed the initial findings. Cooper et al. (1997) gave some theoretical insight on why the particles from these flares could have an effect on rainfall production efficiency. A new hygroscopic flare-seeding programme also was initiated in Mexico in 1996 under the scientific guidance of NCAR of the USA. This experiment was modelled on the South African randomised experiment with the same randomising procedure, seeding flares and pilots that were used locally. The radar that was used in the Mexican experiment was upgraded by the South Africans in order to ensure data compatibility to that applicable in the NPRP. Bruintjes et al. (2003) presented some of the latest results from the Mexican experiment. The fact that the Mexican results were very similar to the South African results and that encouraging results were also obtained from the Thailand hygroscopic seeding experiment, prompted the WMO to arrange a special workshop focusing on hygroscopic seeding and how to proceed with the further development and evaluation of the technology (WMO, 2000). More or less at the same time Bruintjes (1999) reviewed all cloud-seeding experiments to date and highlighted hygroscopic flare seeding as particularly promising.

For the sake of completeness and to show the remarkable consistency in results of past experiments, the quartile analyses from the NPRP randomised seeding experiment, the Mexican randomised seeding experiment and the NPRP semi-operational seeding programme are presented in Figs. 1a, b and c. These results are all based on radar-estimated rain mass of the seeded storms and their natural counterparts – randomly selected in the randomised experiments and paired off with storms with similar initial characteristics in the semi-operational experiment (Terblanche et al., 2000).

Randomised experiments vs. operational seeding

In a randomised experiment suitable storms for seeding are selected before the decision is known whether they will be seeded or not. This procedure is similar to the statistical tests often done in the medical fraternity to determine the effects of certain treatments. Through a randomised experiment a data set is compiled with comparable seeded (treated) and control (placebo) storms. Statistical tests can then be performed on the data set to test whether the hypothesis stated before the experiment can be rejected or not and with what strength/level of significance. The zero-hypothesis – that there is no difference due to the treatment – is tested against the stated hypothesised effect. A well-designed statistical experiment is an important component of cloud-seeding experiments as the cloud-seeding effect is often overshadowed by the large natural variability in storms. However, in isolation, statistics do not prove anything, nor do they provide much insight into the physical processes involved. It is for this reason that it is important that statistical results must also be supported by physical measurements and the results from numerical models to gain credibility (as was attempted in the NPRP randomised experiment).

In operational seeding programmes randomised seeding is often ruled out and the question of evaluation becomes extremely complex as there is no randomly selected control group. A control group has to be determined through other means and the procedure used is always open for criticism. Statistical tests can still be applied but should be interpreted differently. In these types of projects statistical significance is only an indication of the "strength" of the difference between the seeded and control groups. However, it is believed that in the approach followed in South Africa, where the analysis of the non-randomised seeding is being compared to the randomised seeding as was done by Terblanche et al. (2000), some credibility is added to the non-randomised results. For example, apart from the similarities in the apparent effect of seeding on the radar-estimated rain mass between the two experiments, it was also found that similar radar-determined properties reacted in a similar chronological sequence in the non-randomised experiment as in the randomised experiment.

Furthermore, despite the fact that a method was designed to do an analysis for non-randomised seeding, this method is only applicable to those storms that were selected for seeding early in their lifetime. This allows a time-of-origin analysis in which storm properties of the seeded and control storms can be compared from the time they were first identified as storm tracks by TITAN. This procedure is well documented by Terblanche et al. (2000) but in this study the TITAN software was used for the first time to conduct the analysis. To date no method exists for the storms that were seeded long after they had developed.

The South African Rainfall Enhancement Programme

Facilities and funding

During the 1997/98, 1998/99 and 1999/2000 summer seasons the operations were dependent on radar coverage provided by the WRC's aging Pacer C-band radar located on the Letaba Estates to the east of Tzaneen. This specific radar is one of only three similar radars built in the US in the early 1970s and the only one that was still operational at that stage. It was found that this old radar was not reliable enough to operate on a continuous basis. Maintenance and spares were growing concerns and it became quite challenging to keep the system operational. Therefore, this radar was only operated during seeding operation and therefore no complete radar storm climatology could be compiled. The SAREP project team highlighted the shortcomings of this radar during the 1998/99 season and suggested that SAWS should consider replacing the Pacer radar with a moth-balled Enterprise radar similar to those used at several other sites in South Africa. This radar was eventually upgraded and installed at the Gateway International Airport in Polokwane in September 2000, just in time for the last SAREP summer season. The site of the Polokwane radar, the area of coverage and the 100 km x 100 km target area are shown in Fig. 2.

TABLE 1
Annual SAREP funding

	1997-1998	1998-1999	1999-2000	2000-2001
CloudQuest contract	R3.5 m.	R2.5 m.	R1.5 m.	R1 m.
SAWS contribution	R1 m.	R1 m.	R1 m.	R1 m.

Fortunately the Enterprise radar at Polokwane was reliable enough to allow 24h operations and to be included in the SAWS National Weather Radar Network. It provided the data necessary to compile a radar-based storm climatology for the region and represented a significant improvement in terms of data availability, coverage of the target area and ease of use in comparison to the Pacer radar. Apart from being used for the first time for the seeding analysis, the TITAN software was also used in SAREP for the first time to compile a radar storm climatology in South Africa. As part of SAREP the storm matching algorithm described by Terblanche et al. (2000) was implemented as an integral part of TITAN in cooperation with Dr Dixon during a visit he had to South Africa.

The aircraft used for seeding were the two SAWS Aerocommander 690A turboprop research aircraft and the WRC's Aerocommander 500S piston engine aircraft. These aircraft were equipped for hygroscopic seeding and with systems to provide their GPS positions during flights to the radar site in real time.

Before the 1999/2000 summer season the aircraft were based at Tzaneen but were then relocated to Polokwane mainly in anticipation of the deployment of the SAWS radar. During the last SAREP season a more optimal situation was achieved in which Polokwane was the base for the project radar, the aircraft and the SAREP operational personnel.

The funding level, which was decided on an annual basis, was considerably lower than that requested in the original proposal. In addition, the budget allocation for several seasons only became available during the summer season, limiting the use of the full convective season for seeding operations. SAWS' contribution to the total programme amounts to about R4m, which brings the total cost of the seeding operations of SAREP to approximately R12.5 m. Table 1 shows the SAREP budget that was paid out on an annual basis to the contracted firm CloudQuest for conducting the flight operations and some of the radar guidance during the seeding operations. Also shown is the contribution made by SAWS.

Seeding operations

Although SAREP was originally planned as a three-year project it was eventually extended for an additional year that included a 3-month seeding period. The reasons for this extension were primarily to take advantage of the newly commissioned radar facilities at Polokwane and to extend the sample size of the seeded storms. The total number of storms seeded before October 2000 was limited. Serious flooding events such as that in February 2000 when seeding operations were stopped and the unstable funding situation contributed to the small sample size.

During the first three SAREP seasons personnel from SAWS manned the radar and the CloudQuest pilots conducted the seeding operations. During the final season and mainly due to the more reliable radar being available at Polokwane, CloudQuest personnel was responsible for both the radar operations – after a short training course – and pilot operations. SAWS personnel handled the data analysis of SAREP with some input from the Centre for Applied Statistics at UNISA.

In short, during a seeding operation the radar operator is

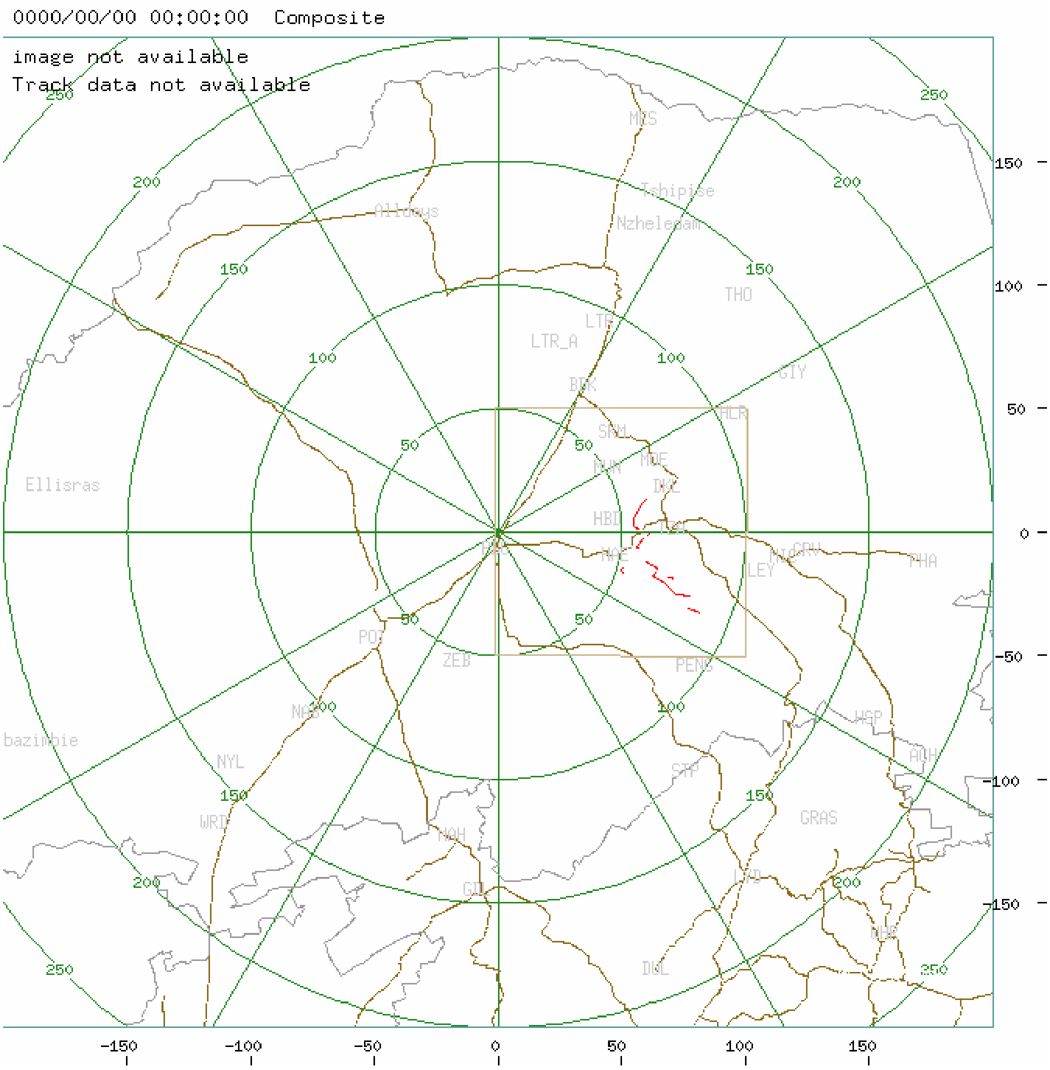


Figure 2
The coverage, to a range of 200 km, provided by SAWS's C-band radar at Polokwane.
Also shown is the square, 100 km X 100 km target area just to the east of Polokwane.

responsible to launch the aircraft to suitable areas of convective development or to suitable candidate storms. The seeding pilot is responsible to confirm whether the candidate storm fulfils the seeding requirement regarding updraft strength, and other visual clues and if so, to deliver the seeding material. Teamwork is extremely important and so are quick reactions to instructions from the radar operator to launch and to reach suitable areas. Table 2 shows the number of cases in each of the SAREP seasons.

Storm-based analysis of seeding effects

TABLE 2
The number of seeding cases in each SAREP season

	1997/98	1998/99	1999/2000	Oct - Dec 2000
Seeded cases	34	7	14	40

A number of practical considerations emerged whilst analysing the storms:

- There were discrepancies between radar operator and pilot logs for a number of cases. Although most of these were resolved, cases where it proved to be impractical or impossible were simply rejected from the analysis.
- The basic selection criteria were not always adhered to when selecting the storms to seed. These marginal selections included:
  (a) Seeding an echo not entirely convective in nature (exhibiting more tropical or stratiform structures with weak updrafts)
  (b) Seeding large mergers and parts of the same complex track, i.e. the issue of spatial case separation
  (c) Seeding left-moving (relative to the steering winds) storms that often spawn severe weather

For the cases referred to under (a) previous analyses have shown that clouds with a more "maritime" character might not respond well to seeding, as the precipitation formation processes in such cloud systems are already efficient. The echoes are spread over large areas, are rather weak and shallow and have only marginal updraft cores. For analysis purposes the cases under (b) are problematic as large complex tracks that include storm mergers become impossible to analyse objectively and the seeding response could be diluted in the large cloud volumes. In addition when conducting a "time-of-origin" analysis, the origin of the complex track is specified and if different parts of the same complex track are seeded as separate cases they trace back to the same point of origin, effectively reducing two cases (or more)

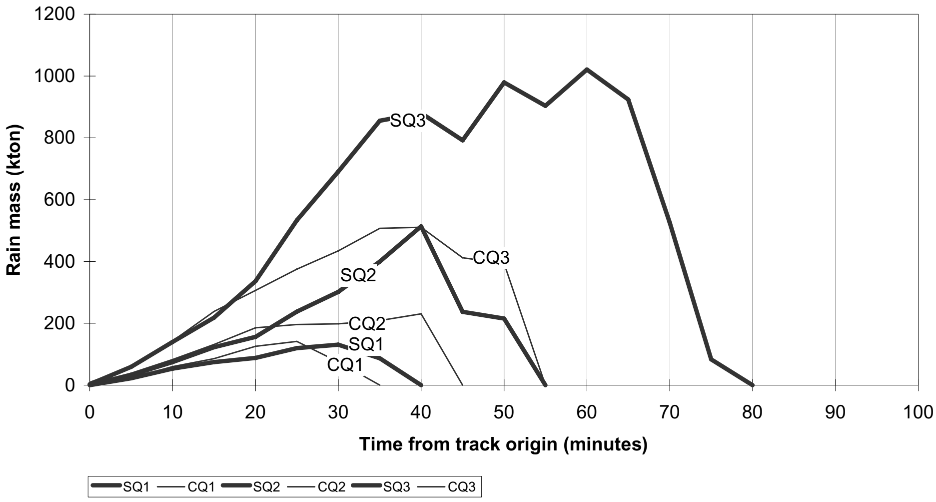


Figure 3
Quartile analysis of rain mass of the 24 Type A storms for the Tzaneen-based data set. Thick lines represent the seeded group for each quartile (e.g. SQ1, SQ2 and SQ3) and thin lines the control group quartiles (e.g. CQ1, CQ2 and CQ3).

into one. Cases mentioned under (c) could result in some serious public relations issues if the seeded storm is perceived to be responsible for damaging weather phenomena (not as a result of seeding but this would of course be the disputed issue). Severe storms are also very persistent which could introduce a positive bias into the seeded storms group. Clearly, in any future programme of this kind, special attention should be given to storm selection procedures. Good co-ordination between experienced radar operators and pilots would go a long way to address this issue.

A further point of concern was the number of misfired flares during the last season of SAREP. Several cases have been rejected because the number of flares that actually burnt is less than or equal to 50% of the total fired.

The 'time-of-origin' analysis is restricted to those storms that were selected for seeding within 30 to 35 min of their time of track origin and which were not affected by the issues mentioned above. They are referred to as Type A storms. Twenty-four of the 55 Tzaneen storms were Type A storms, whereas 13 of the 40 Polokwane cases also met the requirements for Type A storms. It can be seen that there was a slight deterioration in the ratio of Type A storms to total storms seeded between the Tzaneen and Polokwane data sets. This is probably related to the radar operations being transferred from the experienced SAWS personnel to the CloudQuest personnel at the time the Polokwane radar was commissioned.

The quartile analysis of radar-estimated rain mass in kiloton (kt) for the 24 Type A Tzaneen storms and their controls are shown in Fig. 3. The rain mass is plotted against the centre time of the 5min interval in which the radar collects volume-scan data. This time is referenced to the volume scan just prior to storm origin. It can be seen that especially the median and third quartile of the seeded group show large increases in radar estimated rain mass when compared to the controls. Also of note is the apparent increase in storm lifetime in the seeded group.

The additional 13 Type A cases from the final season is a small sample and the results obtained from this group should be viewed with caution. However, the storm-matching algorithm used for this analysis benefited from the good quality 24 h radar data collected at Polokwane and the controls found were well matched. The global storm lifetime characteristics parameter that consistently showed significance at $P<0.05$ (recalling how statistical significance should be interpreted in a non-randomised experiment) for all the quartiles in the Polokwane data is the parameter indicating whether a storm is "top heavy" or not. Mather et al. (1997b) also alluded to a similar finding in the exploratory analysis carried out as part of the NPRP randomised experiment analysis. This feature in a storm is an indication of development and an efficient rainfall formation process.

Figure 4 shows the quartile analysis of the radar-estimated rain mass (in kt) of the 13 Type A storms for the final season using the Polokwane radar. Again the increase in rain mass in the seeded quartile is clearly visible. In addition the differences between the seeded and control storms were found to be statistical significant ($P < 0.05$) in the 45 min interval for the first quartile. No differences in any time interval proved significant for the median storms and only the 50 min interval showed a significant difference for the largest storms.

Of greater interest is the ensemble of cases for both operational areas. In merging these data sets the differences in radar data quality and availability have to be kept in mind. The cases and their matches were considered without any assumptions in this regard and combined to give 37 Type A storms. Figure 5 shows the results of the quartile analysis of this combined set.

The differences between the seeded and control time series show enhanced statistical significance for the observed differences. Statistically significant differences ($P < 0.05$) were now detected at 25, 30 and 35 min for the 1st quartile. Similarly, the differences were significant at 45 and 50 min for the median and at 50, 60 and 65 min for the 3rd quartile. For the 100min interval from time of origin, the ratio between accumulated arithmetic mean rain mass for the seeded and control storms came to 2.08 indicating an average increase in rain mass of ~8000 kt (108%) which corresponds to just more than a doubling in rain mass. For the 37 storms analysed it amounts to about 296 X 10^6 m^3 of additional radar-estimated rainfall and referring back to the total cost of the programme as given in Table 1, this implies a cost of ~R0.04 per m^3. If this type of effect occurred in all 95 storms seeded as part of SAREP, the benefit/cost ratio could be even more favourable.

In the combined data set, the global storm lifetime characteristic parameters show consistency with the "top-heaviness" of the storms now reaching a significance of $P < 0.025$. This observation forms a link to the previous experiments and their results. It must be stressed that the sample size of 74 is still small (37 seeded and 37 controls). However, the results are consistent with those published by Terblanche et al. (2000) for the semi-operational work done towards the end of the NPRP (sample size 120; 60 seeded and 60 selected controls) and that by Mather et

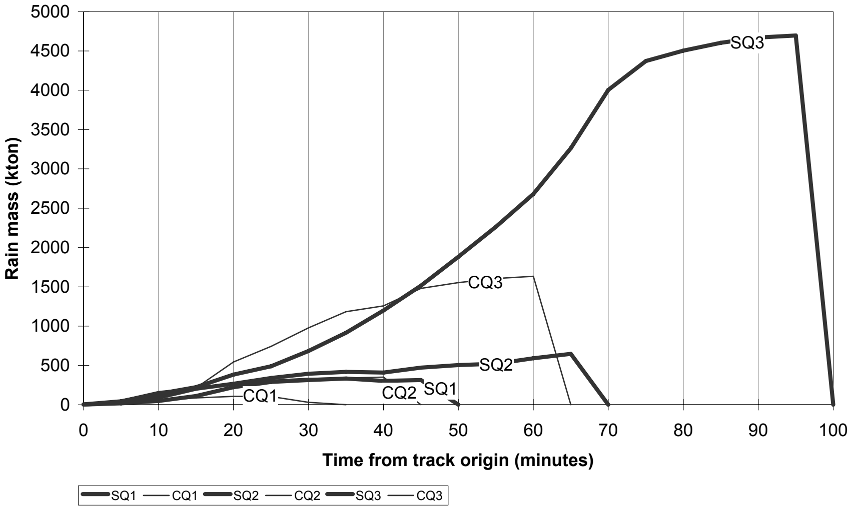


Figure 4
As in Figure 3 but the quartile analysis of rain mass of the 13 Type A storms for the Polokwane-based data set

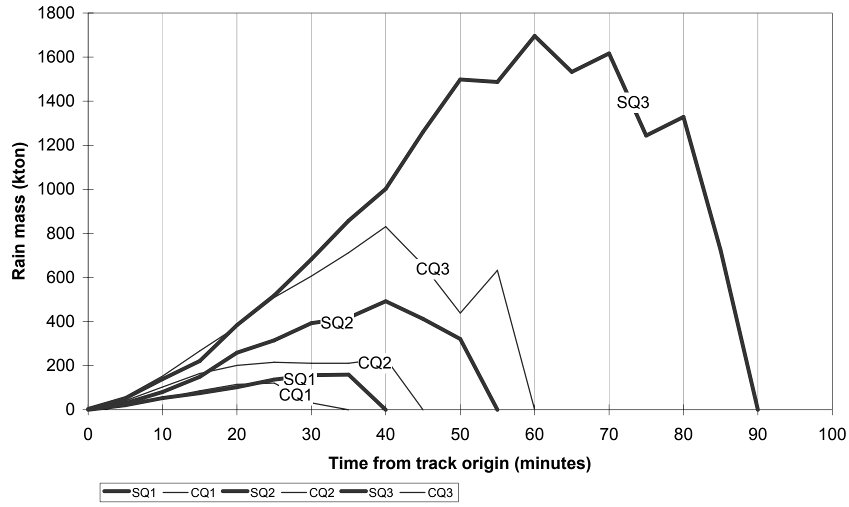


Figure 5
As in Figure 3, but the quartile analysis of radar-estimated rain mass of the 37 Type A storms for the combined Tzaneen and Polokwane-based data sets

al. (1997b) for the randomised experiments (sample size of 127; 62 seeded and 65 controls).

The following conclusions can be drawn from the SAREP analysis:

- The rain mass quartile analysis of the Type A storms shows consistency with similar analyses done in the past for the NPRP and Mexican data sets
- The rain mass arithmetic mean analysis indicates that the seeded storms produced about twice (seed to control ratio of 2.08) as much radar-estimated rainfall as the control storms
- Case selection for the analysis was not ideal. Only 39% of the total declared SAREP cases are Type A storms that allows a time-of-origin analysis

As yet, no feasible way of objectively analysing the other storms has been found. Nevertheless, the subset of Type A storms appears to provide an indication of the same observed trends as published previously. It is also encouraging to note that the statistical measures strengthen with increasing sample size, i.e. by combining the data sets from Tzaneen and Polokwane. Therefore, the results from this study, when seen in conjunction with those from similar earlier projects, are important as it further strengthens the conviction that the hygroscopic flare-seeding technology has a beneficial effect on the radar-estimated rain production from convective storms. This technique of pooling results has become a convincing method to strengthen and demonstrate seeding effects (List, 2005).

Storm climatology

The average seeded SAREP storm produced about 16 000 kt of rainfall over its lifetime compared to the 8 000 kt of the controls. The first question that comes to mind is how many of these storms would have to be seeded to achieve say a 10% increase in area rainfall over the target area. Simple calculations show that about 1.25 of the treated storms will be required to produce an additional 1 mm on average over the whole target area. Therefore if the seasonal rainfall of the target area amounts to 600 mm, it can easily be shown that 75 seeded storms would produce a 10% increase in area rainfall.

TITAN was used to analyse the storm tracks that affected the target area for the 7-month period, October 2000 to April 2001. A storm track is defined as a radar echo that exceeds the 30 dBZ level for at least 3 volume-scans (15 min). These are the typical radar properties of candidate storms that might be considered for seeding.

Figure 6 shows the total number of these storms per month for the period under consideration. For the whole 2000/01 season 2 174 of such storm tracks were identified that affected the 100 km x 100 km target area. The monthly values varied between 90 and 540. For the total radar area to a range of 200 km from the radar, 16 726 such storm tracks were detected.

Figure 6
The number of storm tracks that affected the target area as identified per month for the period October 2000 to April 2001

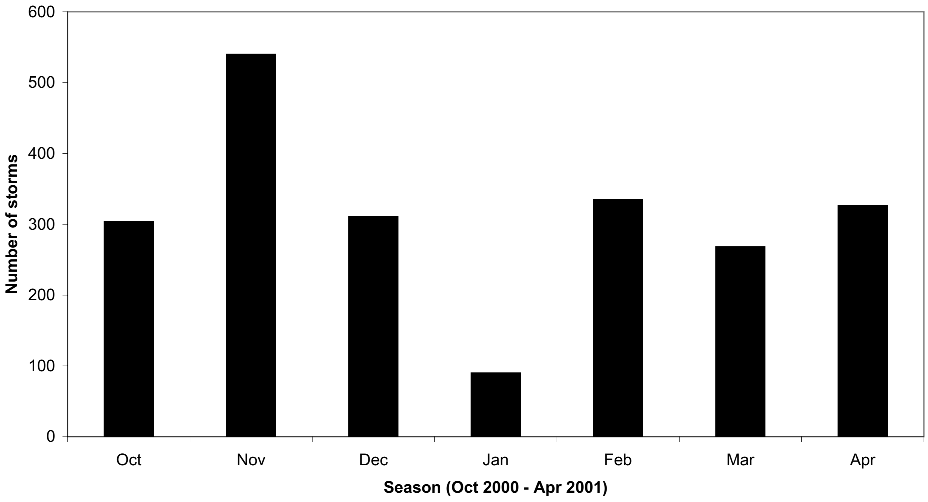
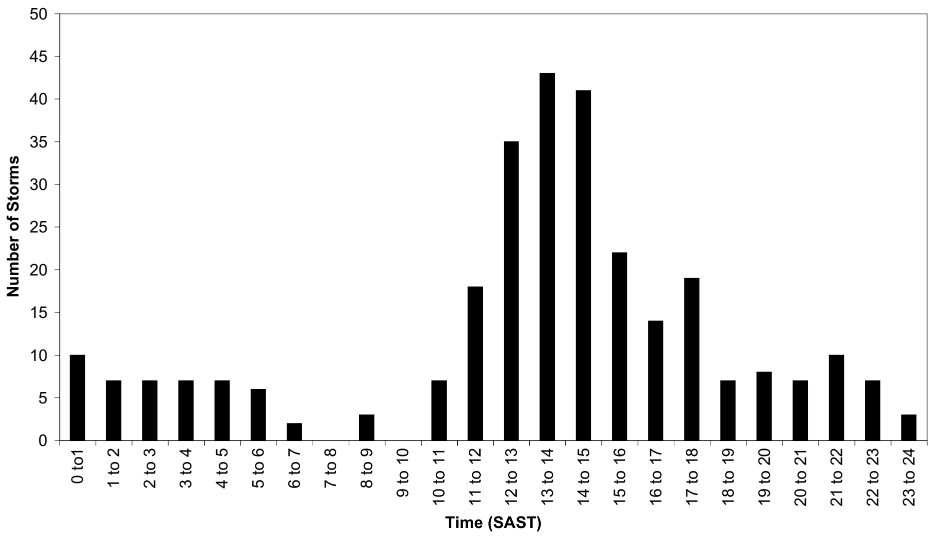


Figure 7
The time of the day (SAST), in hourly intervals, in which the 290 legitimate storm tracks developed



In order to relate the rain-producing characteristics of the identified 2 174 storm tracks to those that were seeded, the following approach was followed: The accumulated rain mass of each of the quartiles of the control storms of the Polokwane-based data set from October to December 2000 was determined. This amounted to 404 kt for the 1st quartile, 956 kt for the 2nd quartile and 11 423 kt for the 3rd quartile. Using these values and calculating the accumulated rain mass of each of the identified storms that affected the target area during the season, it was found that about 13% (290 storm tracks) produced more rain than the 1st quartile of the controls, 10% (217 storm tracks) more than the 2nd quartile and 4.3% (93 storm tracks) more than the 3rd quartile. These findings indicate that probably only 290 of the storm tracks identified (those larger than the 1st quartile of the controls) could be considered as legitimate candidates for seeding. In addition, apart from a slight bias towards storms in the interval between the median and the 3rd quartile, the accumulated rain mass distribution in the 290 storms corresponds quite well with the control group as can be seen by the more or less similar number of storms in each quartile interval. On the other hand, the storms selected for seeding were actually representative of the larger storms in the total seasonal population and as the seeding effect is quite pronounced on the large storms it can probably be transferred to the 290 legitimate storm tracks. These calculations also highlighted the fact that the largest 23 storm tracks of the season contributed about 50% of the rainfall of all the storm tracks. As can be seen from Fig. 5, the largest reaction due to seeding was from the largest storms in the sample but it remains to be proven that there is no limit regarding size on seeding effect.

Figure 7 shows the time of development of the 290 legitimate storm tracks reference to South African Standard Time (SAST). There is a distinct peak that coincides with the diurnal peak in solar radiation. Seventy-three percent (212) of the identified storm tracks originated in the daylight hours between 06:00 SAST to 19:00 SAST with the period between 13:00 and 15:00 SAST being the most active as almost a third of the daylight storms develop in these 2 h.

Despite the assumptions made in the above arguments, the authors feel confident that a 10% enhancement in area rainfall is feasible through an efficient cloud-seeding experiment. Due to the amplifying and non-linear relationships between rainfall on the one hand, and biological and hydrological processes on the other hand, a 10% increase in area rainfall will have considerable socio-economic benefits as has been indicated by Görgens and Jewitt (1995). There appear to be enough candidates for seeding and if only 1 out of 3 of the daylight storms could be seeded it should still be possible to treat the 75 storms required. The fact that such large portions of the candidate storms develop in the 2 h period between 13:00 SAST and 15:00 SAST will have to be considered carefully regarding the equipment, manpower and logistics of any operational programme.

Conclusions

SAREP has produced cloud-seeding results that show similarities to the findings of three previous hygroscopic flare-seeding programmes. It is becoming an acceptable method to pool results from different but similar seeding experiments to increase the confidence in the findings. For the period 1997 to 2001, 95 storms were seeded in the Limpopo Province. In the first 3 seasons, a C-band radar near Tzaneen supported the programme and in the last season this support was provided by a C-band radar in Polokwane. Of the 95 storms seeded, 37 storms were seeded early in their lifetime and this allowed a 'time-of-origin' analysis. The outcome of this analysis can be summarised as follows:

- All 3 quartiles in the quartile analysis show a systematic increase in radar-estimated rainfall from the seeded storms
- The average increase in radar-estimated rainfall comes to 108%, which corresponds to a doubling in storm rainfall
- This increase amounts to about 8 000 kt of additional radar-estimated rainfall per seeded storm
- Taking the ~R12.5 m. cost of the programme into consideration, the results indicate that the cost of additional rain-water from the 37 storms analysed could be as low as R0.04/m^3
- Assuming the seeding effect, it would require that about 75 storms be seeded over the 100 km x 100 km target area to achieve a 10% increase in area seasonal rainfall.

The Polokwane radar, being operated on a 24 h basis, allowed a radar-based storm climatology to be compiled for the period October 2000 to April 2001. The findings, which support the notion that there are enough storms available for seeding to realise a marked effect on area rainfall, were as follows:

- 290 legitimate storm tracks, to be considered as seeding candidates, occurred over the 100 km by 100 km target area during the season
- 212 of these storm tracks occurred during daylight hours with a peak occurrence between 13:00 SAST and 15:00 SAST.

Despite the assumptions made in this study and the various practical problems encountered, it is the view of the authors that the hygroscopic seeding technology holds much promise as a viable method to augment water resources in South Africa and many other regions of the world. Future areas of research and development should include:

- Investment in a modern research-class weather radar for South Africa to improve the understanding of cloud processes of relevance to rainfall enhancement and to support studies on the relationship between radar estimated rainfall and that measured at ground level
- Refinements in the storm selection criteria
- The research into methods to analyse the seeding effects in storms that were not selected early enough in their lifetimes to allow a 'time of origin' analysis
- The development of new methods to deliver seeding material effectively and cost- efficiently.

Acknowledgements

SAREP was funded by the South African Weather Service, the Department of Water Affairs and Forestry, the Department of Agriculture and the Department of Science and Technology. The authors extend their appreciation to the personnel of the South African Weather Service and CloudQuest who contributed to SAREP for their dedication and excellent teamwork.

References

BIGG EK (1997) An independent evaluation of a South African hygroscopic cloud seeding experiment (1991-1995). *Atmos. Res.* **43** 111-127.

BRUINTJES RT (1999) A review of cloud seeding experiments to enhance precipitation and some new prospects. *Bull. Amer. Meteor. Soc.* **80** (5) 805-820.

BRUINTJES RT, BREED DW, FOOTE BG, SALAZAR V, FOWLER T, BROWN BG and DIXON MJ (2003) Program for the augmentation of rainfall in Coahuila (PARC): Overview and results. *Proc. 8th WMO Scientific Conference on Weather Modification*. Casablanca, Morocco. 103-106.

COOPER WA, BRUINTJES RT and MATHER GK (1997) Calculations pertaining to hygroscopic seeding with flares. *J. Appl. Meteor.* **36** 1449-1469.

DIXON MJ and WIENER G (1993) TITAN: Thunderstorm identification tracking, analysis and nowcasting - a radar-based methodology. *J. Atmos. Ocean. Technol.* **10** (6) 785-797.

GÖRGENS AHM and JEWITT GPW (1995) Can Vaal Dam basin runoff be augmented by convective cloud seeding? *Proc. 7th South African National Hydrological Symposium*, Rhodes University, Grahamstown.

LIST R (2005) Personal communication. University of Toronto, Canada.

MATHER GK and TERBLANCHE DE (1993a) The National Precipitation Research Program. WRC Report No 133/8/93.

MATHER GK and TERBLANCHE DE (1993b) Rain augmentation research in South Africa. *S. Afr. J. Sci.* **89** 22-23.

MATHER GK and TERBLANCHE DE (1994) Initial results from cloud seeding experiments using hygroscopic flares. *Proc. 6th WMO Scientific Conference on Weather Modification*. Paestum, Italy. 687- 690.

MATHER GK, TERBLANCHE DE and STEFFENS FE (1997a) The National Precipitation Research Program: Final Report for the Period 1993-1996. WRC Report No 726/1/97.

MATHER GK, TERBLANCHE DE, STEFFENS FE, and FLETCHER L (1997b) Results of the South African cloud-seeding experiments using hygroscopic flares. *J. Appl. Meteor.* **36** 1433-1447.

SHIPPEY K, GÖRGENS AHM, TERBLANCHE DE and LUGER M (2004) Environmental challenges to operationalisation of South African rainfall enhancement. *Water SA* **30** (5) 636-640.

SILVERMAN BA (2000) An independent statistical re-evaluation of the South African hygroscopic flare seeding experiment. *J. Appl. Meteor.* **39** 1373-1378.

TERBLANCHE DE, STEFFENS FE, FLETCHER L, MITTERMAIER MP and PARSONS R (2000) Toward the operational application of hygroscopic flares for rainfall enhancement in South Africa. *J. Appl. Meteor.* **39** 1811-1821.

WMO (2000) Report of the WMO International Workshop on Hygroscopic Seeding. WMP Report No 35, World Meteorological Organization, Geneva, Switzerland. 68 pp.