WATER RESEARCH COMMISSION

THE GENERATION OF A SPATIALLY DISTRIBUTED DAILY RAINFALL DATABASE FOR VARIOUS WEATHER MODIFICATION SCENARIOS

by

Alan William Seed

Directorate of Hydrology
Department of Water Affairs and Forestry
Private Bag X313
Pretoria

September 1992

ISBN 1 874858 56 X
WRC Report No 373/1/92

CONTENTS

PART 2 : MODELLING

EXECUTIVE SUMMARY

THE GENERATION OF A SPATIALLY DISTRIBUTED DAILY RAINFALL DATABASE FOR VARIOUS WEATHER MODIFICATION SCENARIOS

by

Alan Seed

Motivation

Research into the possibility of enhancing the summer convective rainfall by means of cloud seeding has been motivated by the forecast that the demand for water in South Africa will exceed supply by the year 2020. The Water Research Commission contracted Görgens and Rooseboom (1990) to plan the research effort needed to quantify the impact of an operational weather modification programme. The Görgens and Rooseboom report recommended that a number of desk-studies be undertaken in order to assess the likely impact of weather modification in the fields of water resources, agriculture, and forestry. A basic requirement for any such desk-study is a set of natural and modified rainfall series that could serve as an input into numerical models.

Objectives

The objectives of this project are to develop models required to generate sequences of natural daily rainfall, and thereafter modify this natural rainfall to simulate a weather modification programme. The models developed to simulate the weather modification programme must be based on daily rain gauge data, since this is the only rainfall data available over a large fraction of the study area. A further requirement is that it must be possible to stochastically generate new sequences of spatially distributed rain fields, and to be able to impose the weather modification simulations onto these data.

Summary of results

High resolution radar rainfall data from the Carolina and Bethlehem weather radar observatories were used to simulate a weather modification programme. Major results from these simulations based on 54 days of radar data are as follows:

1) The percentage increase in mean areal daily rainfall does not appear to be a function of the mean areal daily rainfall, but rather the mean duration of the storms that develop on the day.

2) The frequency distribution of the increase in mean areal daily rainfall was found to fit a lognormal probability distribution.

3) Based on an analysis of the 28 days in the Bethlehem data set, the mean increase in mean areal daily rainfall was 16%, assuming the storms were seeded at the time of the first echo. However, if the storms were seeded 15 minutes after the first echo, which is possible considering the need to first track the storm and thereafter fly to the storm's location, the mean increase in mean areal daily rainfall was reduced to 10%.

Once the effect of weather modification on mean areal daily rainfall had been quantified, it was possible to develop a model to simulate a weather modification programme using daily rain fields derived from gauge measurements. Rain gauge data were used to classify the historical rain days into dry, scattered, and general rain days based on the fraction of rain gauges measuring rainfall. Weather modification was assumed to take place only on scattered rain days during the summer months, the increase in mean areal daily rainfall for each scattered rain day was drawn from a lognormal probability distribution. The increase in annual rainfall was found to be 7%, based on a 10-year simulation.

The stochastic model developed to generate sequences of spatially distributed rain fields is as follows:

1) Generate a sequence of historical daily rain fields using rain gauge data.
2) Classify each day in the record as dry, scattered, and general rain days.
3) Calculate the transition probabilities between these three states.
4) Use a Markov chain model to generate new sequences of dry, scattered, and general rain days.
5) Build a new data set with this sequence of rain day states, selecting an appropriate rain day at random from the historical record.

The model was tested using rain gauge data for the area covered by the Carolina radar. The model was found to reproduce the probability distribution for total summer rainfall, although the intra-seasonal variability was not adequately modelled.

Conclusions

The increase in mean areal daily rainfall resulting from a weather modification programme will be almost unmeasurable, even with a well calibrated weather radar, except on a few highly successful days. The issue of how to verify a weather modification experiment with rainfall measurements therefore needs far more attention, in particular, the relocation of the Bethlehem radar to a more favourable site and the acquisition of better radar hardware should be considered.

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

ACKNOWLEDGEMENTS

The author is indebted to the following persons and organisations:

Professor G.G.S. Pegram of the University of Natal for much assistance and many helpful suggestions
Mr G. Mather of CIC for the Carolina radar data and assistance with aspects of weather modification
Mr D. Terblanche of the Weather Bureau for the 6-week radar data collection effort and assistance with aspects of weather modification
The Weather Bureau for the daily rainfall data
Dr H. van Vliet of the Department of Water Affairs and Forestry for supporting the project
The Water Research Commission Steering Committee for many helpful suggestions
Mr W. de Goede of the Department of Water Affairs for the final lay out of the report.

A.W. Seed
Directorate of Hydrology
DWAF
Pretoria

August 1992

CHAPTER 1

INTRODUCTION

Gordon's great insight was to design a program which allowed you to specify in advance what decision you wished it to reach, and only then give it all the facts. The program's task was simply to construct a plausible series of logical-sounding steps to connect the premises with the conclusion.

The REASON package, in Dirk Gently's Holistic Agency, Douglas Adams.

The Bethlehem Weather Modification Experiment (BEWMEX) was started during 1969 as a joint venture between the Department of Transport (Weather Bureau) and the Department of Water Affairs. In 1979 the project was split into two sections, with the Hydrological Research Institute starting the Bethlehem Run-off Augmentation Research (BRAR) to develop the hydrological components of the experiment, whilst the BEWMEX project undertook the meteorological research. The objectives of BRAR were primarily to determine the effect of cloud seeding on the run-off in the Vaal Dam catchment. An experimental catchment of 372 km^2 was established east of Bethlehem in the Wilge catchment. A network of some 30 tipping-bucket rain gauges were installed to measure 5-minute rainfall depths and a detailed hydrological data base for the experimental catchment was established. The experiment was finally stopped by the Department of Water Affairs in 1988 with the impact of weather modification on run-off still largely unknown.

Weather modification research started in Nelspruit as an operational hail suppression programme funded by the local tobacco cooperative. This programme ran from 1971 until 1981. Thereafter, the Water Research Commission funded two phases in the Programme for Atmospheric Water Supply (PAWS) to evaluate the potential for increasing summertime convective rainfall in the eastern Transvaal. A randomized seeding experiment was conducted by the PAWS research team until the end of 1989. Thereafter a decision was made to merge the two weather modification research teams into a single National Precipitation Research Project in 1990, and to focus more clearly on understanding the cloud micro-physical processes at work in convective storms.

Weather Modification in South Africa has been driven in the past by the forecast that the demand for water in South Africa will exceed supply by the year 2020 (Alexander 1982; Mason-Williams, 1984; Simpson Weather Associates and Cansas International Corporation, 1986). However, with the exception of the BRAR project, very little work has been undertaken to evaluate the impact of cloud seeding on the likely beneficiaries. In 1989 the Water Research Commission contracted Görgens and Rooseboom (1990) to undertake a study designed to plan the research effort needed to quantify the impact of an operational weather modification programme on end users. The Görgens and

Rooseboom report recommended that a number of desk-studies be undertaken in order to assess the likely impact of weather modification in the fields of water resources, agriculture, and forestry. A basic requirement for any desk-study is a set of natural and modified rainfall series which could serve as input into numerical models. The aim of this project then is to develop the models and data sets needed to generate a time-series of modified and natural daily rain fields.

The report consists of two sections, the background section uses radar data to estimate the effect of weather modification on the mean areal daily rainfall. There after the modelling section develops the models needed to simulate a weather modification programme and generate new sequences of daily rain fields. In particular,

Part 1: Background

> Chapters 2 and 3 deal with preliminary details regarding the selection of the test sites and various aspects of rainfall that affect the selection of the methods used later in the report.
>
> Chapter 4 discusses the processing of radar data needed to estimate the effect of cloud seeding on the mean areal daily rainfall.
>
> Chapter 5 presents the results of the simulations using an assumed seeding effect.

Part 2: Modelling

> Chapter 6 introduces the models used for the simulation of a weather modification programme and the generation of new sequences of daily rain fields.
>
> Chapter 7 covers the generation of the rain fields from rain gauge data.
>
> Chapter 8 deals with the implementation and verification of the models.

Part 1
Background

CHAPTER 2

SELECTION OF THE STUDY AREA

The selection of the test area for this study depends on both the availability of radar data, and the variety of end-user activities. Görgens and Rooseboom (1990) identified three candidates for the study area viz. the
Wilge,
Upper Crocodile, and
Usutu/Upper Vaal catchments.

This chapter will assess the quality of the radar data and the variety of activities within each of these three catchments, and will conclude with a selection of the most suitable site as a test area.

2.1 Wilge Catchment

The Wilge Catchment is covered by the Bethlehem radar, however the eastern edge of the catchment is just outside the optimal range of the radar. The historical data did not record the full 360 degree sweep of the antenna since data were not captured while the radar antenna was being elevated to the next scanning angle. Also, the radar site is not ideal with trees and low hills to the south partially blocking the lowest elevation scan. The antenna control and signal digitization systems were modernized in 1991. The antenna programme now takes four minutes to complete a cycle. The row of nearby trees was partially felled in November 1991, further improving the quality of the data.

During December 1991 and January 1992 the Bethlehem radar was operated continuously during two three-week sessions. The data set arising from this special data collection effort represent for the first time in South Africa a complete record of rainfall during two three-week periods. Of the three areas, the Wilge catchment has the least potential for forestry, which is possibly the major beneficiary of a rainfall stimulation programme.

2.2 Crocodile Catchment

The Crocodile catchment area is covered by the radar at Nelspruit. Data were recorded and archived during seeding experiments during the PAWS experiment. However, the site of the radar was considered to be far from ideal for rainfall measurements (Ematek and CloudQuest, 1990). Surrounding hills forced the use of a three degree base scan angle, but there was partial blocking of the radar beam even at this elevation. The high base scan restricts the useful range of the radar. The radar data were recorded at 7-minute intervals if the entire 360 degree sweep of the antenna was digitized, which is fairly slow for the type of data analysis to be undertaken.

2.3 Upper Usutu Catchment

Data from the Carolina radar covers the upper Usutu catchment, and parts of the Upper Vaal and Upper Crocodile catchments. The area includes existing prime forest areas as well as areas that could be suitable for afforestation if rainfall stimulation is successfully implemented. The Carolina radar has a base scan set at 1.5 degrees. The data are recorded at 7-minute intervals unless the radar is set to scan a sector of the full circle.

A major disadvantage in the selection of the Carolina site is the short radar record, viz. 40 afternoons of operations during a period of three summers. It is depressing that two decades of weather modification research at two independent sites has yielded so little continuous radar data of good quality. This short record is still useful however. Simpson Weather Associates and Cansas International Corporation (1986) found that the storm track characteristics for the Nelspruit data did not show a large inter-seasonal variability, leading to the conclusion that even one summer of data could provide a useful sample of convective storms. The Carolina radar was only operated for a few hours a day during the afternoons on which cloud seeding missions were undertaken. This was primarily as a result of the radar operator having to drive from Nelspruit to Carolina on days of cloud seeding operations. The radar data usually covered the period from 12:00 to 16:00 hours.

2.4 Conclusions

To conclude then, the area under the radar at Carolina was selected as the main study area because :
a) the radar data set is considered to be adequate, although of a limited duration, and
b) the radar covers the upper Vaal, the Usutu, and a portion of the upper Crocodile catchments which have been previously identified as the most suitable catchments for rainfall stimulation impact studies.

The weather modification simulations were repeated using the Bethlehem radar data set and the results were compared with the results from the simulations using the Carolina data set.

CHAPTER 3

RAINFALL CHARACTERISTICS THAT HAVE A BEARING ON SIMULATING A WEATHER MODIFICATION OPERATION

It is an important and popular fact that things are not always what they seem.

The Hitch Hikers Guide to the Galaxy. Douglas Adams.

The occurrence of seedable rainfall is an important factor in determining the success of a rainfall stimulation programme. Wide-spread general rain days are not candidates for a cloud seeding operation since, in general, the micro-physical processes that are at work during these events are already highly efficient. Convective storms are therefore the only rainfall systems considered to be suitable for cloud seeding. The rain flux available to a weather modification programme also depends on the fraction of the rainfall that falls during the daylight hours since the aircraft need to visually identify the storms to be treated.

This Chapter will therefore discuss methods used to partition historical rain gauge data into seedable and non-seedable rain days. Thereafter factors influencing the diurnal variation of convective rainfall in the Bethlehem and Carolina areas will be reviewed. Finally, the seeding scenario reported by Görgens and Rooseboom (1990) will be adopted for this study.

3.1 Classification of seedable and non-seedable rain days

An early classification proposed by Hudak et al. (1978) for the BEWMEX project was based on cloud formations associated with convection. The classification scheme is listed in Table 1. Clearly, this classification is not helpful when attempting to classify rain days on the basis of rain gauge data. To address this problem, Court (1979) attempted to find a correlation between the weather type as defined in Table 1 and the fraction of rain gauges in the area reporting rain based on a 68 rain gauge network covering the BEWMEX operational area (367 km^2 per gauge). Rain days were classified into dry, scattered, isolated, and general rain days after the scheme shown in Table 2.

The main conclusions from the study were:
a) most scattered and isolated days were type 5 days
b) most type 5 and 6 days were scattered days
c) most general rain days were either type 6 or type 4

This implies that as a first estimate, the rainfall pattern classification scheme can be used to differentiate seedable (type 5 or isolated and scattered rain days) from non-seedable rain days (dry or general rain days). A problem with this scheme is that the days on which large storms develop, the days with the highest potential for weather modification, could be miss-classified as general rain days, and thereby be excluded from the set of seedable rain days. Since both scattered and isolated rain days are considered to be seedable, a decision was made to combine these rain days into a single class, called "scattered rain" for this project.

Table 1 Classification scheme proposed for BEWMEX by Hudak et al. (1978)

Type	Description
1	Blue Skies
2	Cumulus Mediocris with tops warmer than -5 C
3	Night-time line storms tracking eastwards
4	General rain
5*	Cumulus developments, with tops colder than -5 C but no hail
6	Cumulus development, tops colder than -5 C with hail

* Type 5 weather is considered to be seedable

Table 2 Classification of rain days using rain gauge data only after Court (1979)

Dry	Less than 3% stations report precipitation
Isolated	Between 3% and 15% of the stations report precipitation
Scattered	Between 15% and 50% of the stations report precipitation
General	More than 50% of the stations report at least than 5mm rainfall

The classification into dry, scattered, and general rain days will be used to partition rainfall into seedable and non-seedable classes since:
a) it is based on rain gauge data which is readily available,
b) it is objective, and
c) the connection to the meteorological situation has already been established.

The frequency of scattered and general rain days as measured by a gauge network is also dependent on the density of the gauge network and the size of the study area. A sparse gauge network will tend to over-estimate the frequency of isolated rain days since many small rain storms would not be adequately sampled by a sparse network (Katsiambirpas and De Jager, 1981). The frequency of general rain days is dependent on the size of the study area, with frequency of general rain days decreasing as the size of the study area is increased.

3.2 Differences between wet and dry years

It is of considerable interest to understand the difference between a "wet" summer and "dry" summer, since one would like to know if the number of cloud seeding opportunities are less during a "dry" year. Also the fundamental differences have a bearing on the methodology used to generate new sequences of daily rain fields. SWA and CIC (1986) investigated the differences in rainfall characteristics between wet and dry years in the Nelspruit area. Their findings were that:

a) Rainfall is organized in approximately the same manner for both wet and dry years with a few days contributing a large amount of rain, typically 12% of the rain days contribute 50% of the rain.

b) The total number of rain days is approximately constant for wet and dry years.

c) There is a greater frequency of days with small amounts (< 2mm) of rain during the dry years.

d) The major difference between wet and dry years is the occurrence in wet years of days with average station rainfall above 20 mm/day (SWA and CIC, 1986).

This would seem to imply that the major difference between wet and dry years is the frequency of general rain days, with the frequency of scattered rain days remaining approximately constant. A wet summer could therefore be caused by the occurrence of more general rain days than normal.

3.3 Diurnal distribution

The spatial distribution of the diurnal variation of convective rainfall is closely linked to the triggering mechanisms for the thunder storms. At Nelspruit it was found that:

> *Examination of the diurnal rainfall distributions indicates that afternoon and evening rainfall are common to gauges on the escarpment. However, as one moves eastward the distributions show shifts of rain into the early morning hours and eventually show very little diurnal variations. This pattern is consistent with the argument that the diurnal variations are primarily tied to mesoscale forcing along the eastern slopes of the escarpment*

(SWA and CIC, 1986).

For the Bethlehem area Steyn and Bruintjes (1990) stated:

> *It is evident that the diurnal distribution in areas where the terrain is fairly flat shows a pronounced peak in first echo development while for the higher terrain to the south of Bethlehem two or more peaks are found. In this area the topography combined with the surface heating acts as a trigger mechanism for the onset of cumulus development.*

The diurnal variation of convective rainfall has been found to depend on local topography and will therefore vary quite considerably over the area covered by a weather radar. It is not possible to develop a detailed spatial description of the diurnal variation for the Carolina area since the radar coverage does not include night observations.

A further complication is that there are significant inter-year differences in the diurnal distribution of rainfall cf Figs 2.5.4, 5, 6, 7 of the SWA and CIC (1986) report (pages 17-18). The diurnal variation on convective rain days during a dry summer could also differ from the diurnal variation of a wetter summer since the storms developing in a drier environment would be expected to develop later in the afternoon (pers. com. Terblanche, 1992). The spatial and inter-seasonal variation in the diurnal variation of convective rainfall has important implications for an operational weather modification programme and therefore warrants careful attention. Unfortunately, there is to date insufficient continuous radar data available to be able to address these problems in a systematic manner. A first estimate of the fraction of convective rainfall falling during the daylight hours in the Nelspruit area was given by SWA and CIC (1986) as 60%. For the Bethlehem area, Maaren (1984) estimated this fraction to be 52%.

3.4 Response of a storm to rainfall stimulation

The validity of the time series of modified rainfall data produced by this project depends largely on the seeding effect used in the cloud seeding simulations. The Bethlehem Weather Modification team have not yet established the effect of cloud seeding on an individual storm. Görgens and Rooseboom (1990) proposed a most likely seeding effect for the Carolina/Nelspruit area shown in Table 3.

Table 3 Most likely seeding effect, Görgens and Rooseboom (1990)

Time after seeding	Rain flux % increase	Storm area % increase	Intensity % increase
0 - 10	0	0	0
10 - 20	0	0	0
20 - 30	15	5	10
30 - 40	25	5	20
40 - 50	50	35	10
50 - 60	55	40	10

The proposed seeding effect indicates that the increase in the rain flux due to weather modification is primarily due to an increase in the storm area. This presents a problem in that it does not seem possible to simulate this effect in a computer program with the kind of accuracy required. An increase of 40% in the area of a storm might appear to be substantial, however, in the case of a storm with a circular echo covering 100 km^2, the diameter of the storm will increase from 19 pixels to 22 pixels assuming 0.6 km pixels. Furthermore, the small intense centre of a storm contributes much of the rain flux, making it even more difficult to increase the rain flux by increasing the storm area. The seeding effect will therefore be assumed to increase the intensities only, but by the amounts indicated by the increase in rain flux.

It is clear then, that the individual storm tracks, sampled at intervals of less than 10 minutes, must form the basis for estimating the effect of weather modification on mean areal daily rainfall. This implies the processing of a considerable quantity of radar data to derive firstly rainfall maps, and thereafter the data base of storm tracks required for the simulations.

CHAPTER 4

RADAR DATA PROCESSING

The effect of weather modification in South Africa is presently quantified in terms of the increase in rain flux for individual storms, whereas the impact studies require the effect to be expressed in terms of mean areal daily rainfall. Cloud seeding was simulated by modifying all the storms in the radar data according to the seeding effect. The natural and modified storm tracks were then accumulated into maps of daily rainfall. The initial intention was to use existing software to generate the rainfall maps and to track the storms. However, it soon became apparent that it would be necessary to develop a new package to process the radar data. This chapter briefly describes the basic radar data processing undertaken to establish the required data sets.

4.1 Introduction to radar rainfall measurement

A radar does not measure the rain intensity directly, but only the intensity of the signal scattered back to the radar by the rain drops. The strength of the returned radar signal can be related to the rain intensity by assuming a drop size distribution and a relationship between the drop size and fall speed. It can be shown that after various simplifying assumptions the returned signal measured by the radar can be related to rainfall intensity by mean of a simple relationship

$$Z = aR^b$$

where
Z is the signal measured by the radar, and
R is the rain rate in mm/hr.

The a and b terms in the relationship can be derived empirically by means of calibrating the radar with recording rain gauges, or by means of an analysis of the rain drop size spectrum for that area. An extensive review of this topic can be found in Grosh (1989), and Hodson (1989). The Carolina radar has been calibrated against a small rain gauge network and the relationship $Z = 200R^{1.6}$ has been found to give reasonable results except in situations where the strength of the radar signal is attenuated by heavy rain occurring between the radar and the gauge network (Mather pers. com., 1991). This relationship will be used to estimate rainfall intensities for both the Carolina and Bethlehem data sets since a detailed radar calibration exercise is outside the scope of this report.

4.2 Constructing the radar rainfall maps

The first step in radar data processing is to extract a horizontal slice of data or CAPPI (Constant Altitude Plan Position Indicator) from the three-dimensional volume-scan data. Thereafter the data are transformed from polar co-ordinates into a cartesian grid of rainfall intensities. Before this can be done, however, decisions need to be made regarding

a) The height of the CAPPI above ground level,
b) The size of the area to be mapped, and
c) The spatial resolution of the CAPPI.

The altitude of the CAPPI depends on the nature of the rainfall being measured and the presence of ground interference at the lower levels. In the case of general rain, the cloud systems are not usually very thick, so a CAPPI set at too high an altitude will not record this low-level rainfall. Furthermore, the interest is in rainfall reaching the ground, not at some height above the ground level, therefore, the CAPPI altitude should be set as low as possible. The selection of an appropriate height for the CAPPI is therefore a trade-off between the need to map rainfall that reaches the ground, and the need to minimize the effect of ground interference which increases at the CAPPI altitude is decreased. For the Carolina data, the altitude of the horizontal slice was set at 3000m above ground level. The Bethlehem radar has nearby hills to the south of the radar that block the lowest elevation scan. The height of the CAPPIS for the Bethlehem radar were also set at 3000m, although a shadow area exists even at this altitude. During PAWS 2 certain storm track properties were analyzed as a function of the range of the track. The results indicated that storm track properties were nearly independent of the range up to 80km, thereafter showed a marked dependence on range. EMATEK and Cloudquest (1990) concluded that

> *A cautious approach to the analysis of storm track data from both sites would be to restrict the average range of storms from radar to 80km or less.*

This implies that the maximum area covered by the Carolina radar is a square, 160km on a side.

The spatial resolution of the radar rainfall maps is determined by both radar specific considerations and the size of the mapped area. The Carolina radar has 600m radar bins, therefore the minimum pixel size is 600m. The raw radar data are in polar coordinates, and must be re-mapped onto a cartesian grid during the mapping stage. The number of polar bins falling within a cartesian pixel is dependent on range of the bin. At some range, depending on the radar beam width and the pixel size, a large number of pixels with no polar data will occur. If the pixel size is set too small for the maximum range to be mapped, too many pixels at the edges of the map will need to interpolated from nearby pixels.

The mapping process therefore consists of three passes, first the radar reflectivity Z for each polar bin is accumulated into the pixels, thereafter, the mean Z for each pixel with polar data is calculated and converted into a rainfall intensity. Finally the pixels with no polar data are assigned the rain rate measured at the polar bin nearest to that pixel. For the Carolina radar, assuming a maximum range of 80km, the pixel size was set at 600m. It is convenient for the rainfall map to be an array not exceeding 256 lines by 256 samples, giving a 150km by 150km study area, centered on the Carolina radar. The maximum range for the Bethlehem radar was thought to be in the order of 100km.

At this range, a 1km pixel was selected, giving a map size of 200 lines by 200 samples.

The Carolina data contains some 2000 CAPPIs captured during 40 afternoons of weather modification operations during the summer months of 1988/1989, 1989/1990, and 1990/1991. Unfortunately, limited data were captured during the 1990/1991 summer due to fire damage. The Bethlehem data set consists of over 4000 CAPPIS taken during the 1991/1992 summer season. Most of the data were captured within two three week periods during December 1991 and January 1992. Some 7 giga bytes of raw radar data were recorded during the six week period. These raw radar data were therefore processed into CAPPIs using the Bethlehem computer facilities, before being transferred to Pretoria for further analysis. A micro Vax 3100 was purchased to process the radar data, a local area network was established between the micro Vax and the computing facilities at the Hydrological Research Institute for access to tape drives, disk space, and image processing facilities. Towards the end of the project the micro Vax was networked to a 486 pc which was used for display and animation of the radar data.

4.3 Tracking storms

The weather modification research team currently uses storm tracking software written by Dixon. The tracks for the Carolina data set were acquired and analyzed in conjunction with the CAPPI data. Several problems with the tracking software became apparent:

a) The software tracks three-dimensional storms whereas the interest for this project is the rainfall on the ground. Not every storm tracked aloft resulted in rain at the lower levels, resulting in tracks that did not leave a rain footprint.

b) Only the aggregate properties of the storm, for example area and volume, were reported. The simulation software would need the pixels that made up the echoes in each track.

c) The software could not cope with mergers and splits in the storm tracks.

The decision was therefore made to develop a new storm tracking package that would meet the peculiar requirements of this project.

The generic approach adopted was to systematically increase the levels of abstraction, moving up from pixels, to echoes, to storm track fragments, and finally to storm complexes. The first step was to identify those pixels in a CAPPI that made up an echo in a CAPPI. An echo was defined as a contiguous set of 20 or more pixels with non-zero rainfall. The position and rain rate of each pixel within each echo for each CAPPI was written to a pixels data base. The number of pixels that make up an echo, the position of the start of the pixel data within the data base, as well as the time and centroid of the echo was written to an echoes data base. The next step was to link the echoes together over time to form storm track fragments. The first echo in a track was assumed to be moving at the mean velocity of echoes of the other tracks active at the time. The position of the echo centroid of each track was forecast for the following

CAPPI using the current echo velocity. Thereafter, the distance from each echo in the following CAPPI to the forecast position for the echo of each track was calculated. The echo closest to the forecast position of each existing track, providing it was less than some maximum distance, was assigned to that track. The echoes that were not successfully assigned to tracks were assumed to be the first echoes of new tracks. Tracks that were not assigned new echoes were assumed to have terminated, and the track was written to the tracks data base and deleted from memory. If two tracks were found to link to the same echo, a merge was assumed to have taken place and both tracks were terminated and written to the tracks data base. The maximum distance between the forecast echo position and the actual echo position was set assuming a maximum velocity error of 45 km per hour. This algorithm resulted in short well-defined track fragments, although a single storm could have more than one track fragment associated with it.

The final stage was to link the track fragments together into storm complexes. A merge was assumed to have taken place between two tracks if the last echo of a track, translated by the velocity of the track overlaps with an echo of the second track. A split was assumed to have taken place if the first echo of a track, extrapolated back in time by the velocity of the track between the first two echoes, overlaps with an echo of the second track. Each complex of tracks was written to a data base, the history of each split and merge within the complex was also recorded for use later by the cloud seeding simulation software.

CHAPTER 5

QUANTIFICATION OF THE EFFECT OF WEATHER MODIFICATION ON MEAN AREAL DAILY RAINFALL

By the time you've sorted out a complicated idea into little steps that even a stupid machine can deal with, you've learned something about it yourself.

Richard MacDuff on the use of computers in: Dirk Gently's Holistic Detective Agency, Douglas Adams.

The quantification of the effect of weather modification, assuming a seeding scenario, is the last chapter in this first section of the report. The modelling approach adopted in the second section will depend on the results reported in this chapter. The first section of the chapter quantifies the fraction of the mean areal rainfall that is able to be enhanced by a cloud seeding programme. Thereafter, the increase in mean areal daily rainfall due to cloud seeding is estimated and modelled as a fraction of the total daily rainfall. It is of considerable interest to be able to identify days on which cloud seeding is most efficient. It follows from the seeding scenario in Table 3 that the maximum increase in rain flux occurs 40 minutes after a storm is seeded. The duration of storms occurring on a day are therefore expected to influence the seeding effect. The final section examines the relationship between the mean duration of seedable storms on a day and seeding effect.

5.1 Seedable rainfall vs total rainfall

Seedable rainfall is defined as that fraction of the total rain flux that is able to be modified by the weather modification programme. The operational constraint that only rainfall occurring during the daylight hours is considered to be seedable was not included in this analysis since no night data were available for the Carolina radar. This implies that the rain flux from all storms older than 20 minutes irrespective of the time of day were considered as seedable rain flux. The number of seedable storms, as well as the mean duration of the seedable storms were also calculated for each day. Table 4 lists these attributes for each day in the Bethlehem data set, while Table 5 lists the days in the Carolina data set. A distribution of the percentage of daily rainfall that is considered to be seedable for both radar sites is found in Figure 1.

5.2 Effect of weather modification on mean areal daily rainfall

Also included in Tables 4 and 5 are the increases in the mean daily rainfall expressed as a percentage of the daily rainfall. Figure 2 shows the percentage increase in mean areal daily rainfall plotted as a function of the mean areal daily rainfall for the Bethlehem and Carolina data sets. From this Figure it is apparent that the seeding effect, expressed as a percentage, is not functionally dependent on the mean areal rainfall, and therefore can be modelled as a random variable. Figure 3 shows the histogram of the frequencies of the seeding effect for the combined Bethlehem and Carolina data sets.

Table 4 Number of seedable storms, mean duration of the seedable storms, and mean areal rainfall for the Bethlehem data set.

date	no storms	mean duration (min)	rain (mm)	seedable %	effect %
2 DEC 1991	21	41.3	0.21	50	24
3 DEC 1991	19	39.2	0.10	27	13
4 DEC 1991	9	51.3	0.08	52	34
8 DEC 1991	18	48.7	0.12	45	17
10 DEC 1991	27	35.6	0.12	27	9
11 DEC 1991	29	63.0	0.24	58	31
12 DEC 1991	26	37.7	0.10	30	10
14 DEC 1991	25	40.6	0.11	48	17
15 DEC 1991	15	37.8	0.06	31	10
16 DEC 1991	22	36.6	0.08	35	13
17 DEC 1991	21	41.2	0.05	43	15
18 DEC 1991	23	44.2	0.16	41	14
19 DEC 1991	28	46.5	0.17	41	17
6 JAN 1992	26	58.7	0.27	57	30
8 JAN 1992	13	41.3	0.08	51	20
9 JAN 1992	26	34.3	0.08	37	10
10 JAN 1992	8	47.0	0.08	55	24
11 JAN 1992	10	71.8	0.30	48	36
13 JAN 1992	30	36.0	0.30	24	8
20 JAN 1992	27	35.8	0.15	38	12
28 JAN 1992	12	49.5	0.05	55	25
4 FEB 1992	5	47.4	0.03	59	19
17 FEB 1992	29	46.5	0.21	49	19
18 FEB 1992	5	41.2	0.05	46	11
19 FEB 1992	23	38.2	0.09	44	17
20 FEB 1992	38	51.9	0.23	46	25
21 FEB 1992	15	42.9	0.07	53	24
27 FEB 1992	6	70.8	0.15	55	30

Table 5 Number of seedable storms, mean duration of the seedable storms, and mean areal rainfall for the Carolina data set.

date	no storms	mean duration (min)	rain (mm)	seedable %	effect %
17 OCT 1988	24	34.3	0.32	33	11
3 NOV 1988	23	54.8	1.12	45	20
9 NOV 1988	21	51.7	1.67	36	18
28 NOV 1988	22	57.9	0.97	10	4
2 DEC 1988	32	38.0	0.31	36	10
5 DEC 1988	11	73.1	1.09	26	12
12 DEC 1988	27	70.4	1.00	39	15
15 DEC 1988	21	33.7	0.32	34	8
21 DEC 1988	41	52.1	1.83	32	14
9 JAN 1989	42	44.9	1.32	39	12
10 JAN 1989	9	65.2	0.40	46	24
11 JAN 1989	20	37.2	0.35	45	16
12 JAN 1990	14	56.9	0.23	52	22
20 JAN 1990	17	47.6	0.44	25	7
25 JAN 1990	18	43.3	0.17	46	23
27 JAN 1990	9	82.4	0.50	15	4
19 MAR 1990	18	45.9	0.41	33	19
20 MAR 1990	17	37.3	0.88	31	9
9 OCT 1990	4	65.3	0.20	59	19
30 OCT 1990	29	53.4	0.48	22	8
3 NOV 1990	16	43.0	0.93	58	25
20 NOV 1990	17	35.8	0.25	10	2
21 NOV 1990	17	56.8	0.68	26	8
22 NOV 1990	7	68.0	0.13	39	17
5 DEC 1990	34	48.1	0.99	24	9
12 DEC 1990	46	51.1	2.26	27	11

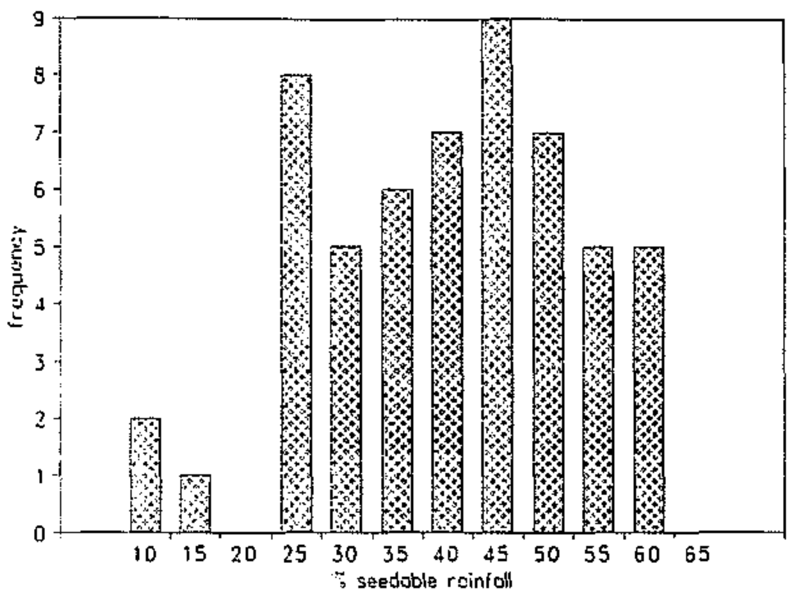

Figure 1 The distribution of the percentage of daily rainfall that is seedable

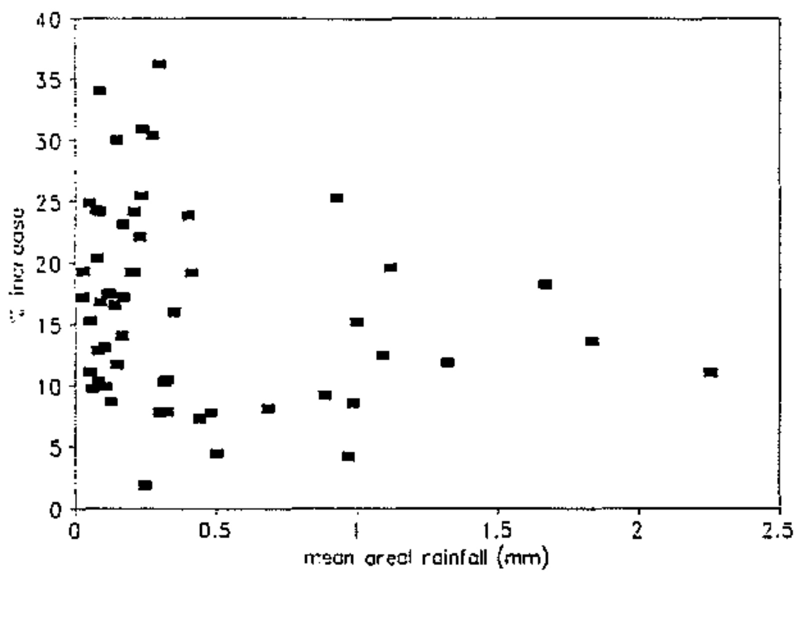

Figure 2 The seeding effect expressed as a percentage increase in mean areal daily rainfall

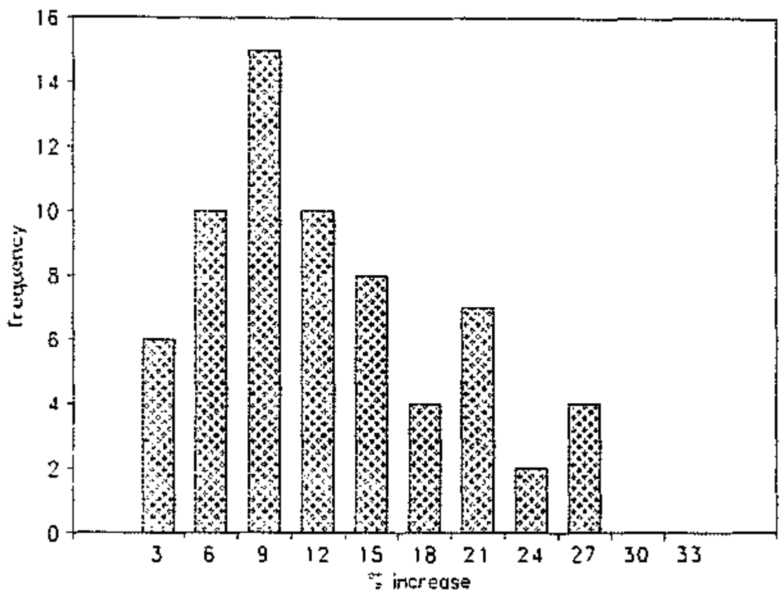

Figure 3 Frequency distribution of the seeding effect for the combined Carolina and Bethlehem data sets

The percentage increase in the total areal rainfall can be modelled as a product of two random variables, viz. the percentage of the total rainfall that is affected by weather modification (using the seeding effect as given in column 1 of Table 3), and the effect of weather modification on this rainfall. The lognormal distribution is applicable in the case where a random variable is thought to be a product of other random variables (Chow et al. 1988). The estimated distribution parameters are shown in Table 6. The Kolmogorov-Smirnov one-sample test (Daniel, 1978) was used to test the hypothesis that the combined data set were drawn from a lognormal distribution with a mean of 2.67 and a standard deviation of 0.56. The test statistic was calculated to be 0.129, and therefore the hypothesis could not be rejected at the 0.05 level of significance.

Table 6 Estimated parameters for a lognormal distribution fitted to the combined combined Bethlehem and Nelspruit data set

log mean	2.67
standard deviation	0.56
number of samples	55
K-S statistic	0.129

5.3 Seeding efficiency

The increase in mean areal rainfall due to weather modification expressed as a fraction of the total seedable rainfall is a measure of the efficiency of the weather modification operation on a day. The most likely factor to influence the efficiency of a weather modification operation is storm duration. Figure 4 shows cloud seeding efficiency plotted against the mean seedable storm duration for the Bethlehem data set. Since the seeding scenario of Table 3 assumed that the increase in rainfall due to seeding is constant at 0.55 after 50 minutes, the efficiency will not exceed this figure. A function of the form

$$E = a + \frac{b}{D-20}$$

is used where
E is the seeding efficiency
D is the mean storm duration for the day, and
a,b are constants.

Table 7 presents the details of the least squares regression results. From this table it can be seen that the seeding efficiency is related to the mean storm duration. The fitted relationship is also plotted in Figure 4. The largest increase in efficiency is when the mean storm duration is increased from 30 minutes to 50 minutes. It would not seem viable to routinely treat storms that are expected to have a life of less than 35 minutes.

Table 7 Estimated parameters for the relationship between mean storm duration and seeding efficiency, using the Bethlehem data

a	58
estimation error	8.47
b	-437.20
estimation error	77.09
number of cases	54
r^2	0.38

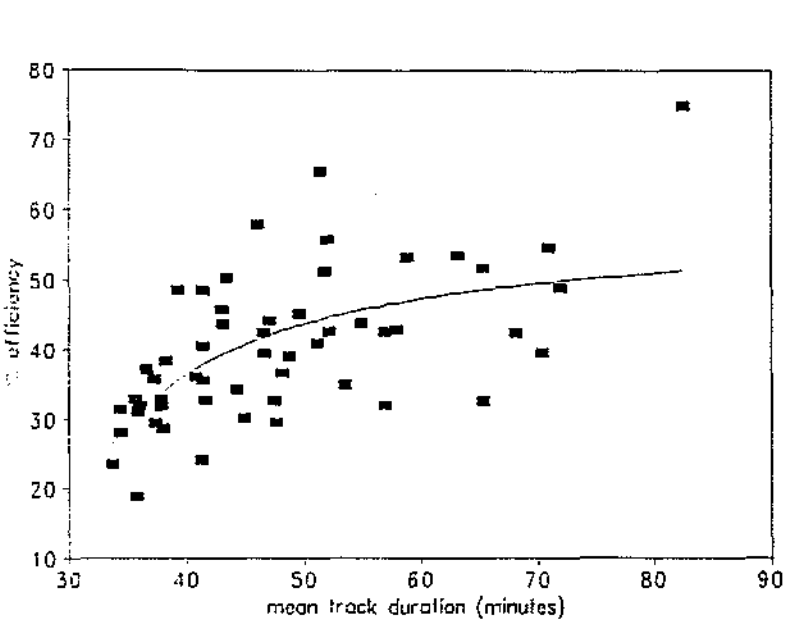

Figure 4 Weather modification efficiency plotted as a function of mean seedable storm duration

5.4 Impact of operational constraints

The above analysis assumed that all the storms that developed over the 24hr period were candidates for cloud seeding. The continuous data from Bethlehem allows one to estimate the impact of restricting the operations to daylight hours only, in this case assumed to be between 06:00 and 18:00 hours. Furthermore, the simulation assumed that the storm was seeded at the time of the first echo, which is clearly optimistic. Experience with tracking the storms has shown that there are a large number of echoes that last less than 10 minutes on any particular day, it is therefore not possible to seed every new echo. An echo would have to be tracked on at least two CAPPIs before a decision to seed could be made, implying at least a 10 minute delay before the storm could be treated. Since there are likely to be a number of tracks to be treated, a further five minutes could elapse before treatment. This implies that the earliest that a storm could be treated after the first echo is of the order of 15 minutes, but certainly not less than 10 minutes using the current technology. The weather modification simulations were repeated, firstly assuming daylight operations only, and then secondly assuming daylight operations with a 15 minute time lag between the first echo and the treatment.

Figure 5 shows the frequency distributions for the seeding effects assuming 24hr operations, daylight operations only, and finally daylight operations with a 15 minute time lag. Table 8 lists the lognormal probability distribution parameters for the three scenarios. It is immediately apparent that the inclusion of the time lag as long as 15 minutes has skewed the seeding effect to the left, while a few cases with a large seeding effect continue to exist. The mean response to weather modification is decreased, but the variability of the response is increased. The number of seedable storms occurring on a day for the Bethlehem data are shown in Figure 6. It can be seen from this figure that usually between 5 and 25 seedable storms develop during the day, although on occasion over 40 seedable storms can develop. It would seem that careful planning is required in order to identify and treat the storms in an operational weather modification programme.

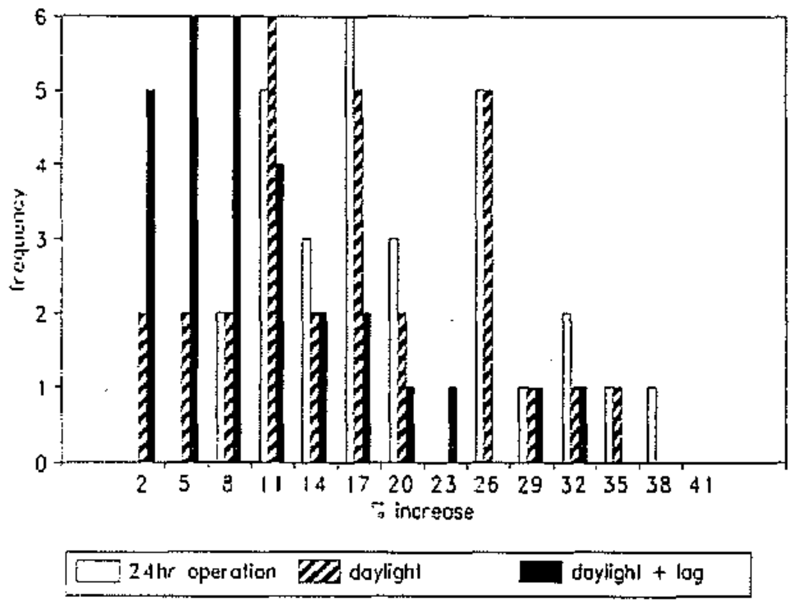

Figure 5 Seeding effect on the Bethlehem data assuming a) 24hr seeding, b) daylight only seeding, and c) daylight only seeding with 15min lag

Table 8 Estimated parameters for a lognormal distribution fitted to the seeding % increase in mean areal daily rainfall assuming:
a) no restrictions on the selection of storms,
b) daylight weather modification operations only, and
c) daylight operations with a 15 minute delay between the first echo and treatment of the storm.

	a	b*	c
mean	2.864	2.627	1.989
standard deviation	0.430	0.633	0.866

* These parameters where used in the simulations of Chapter 8

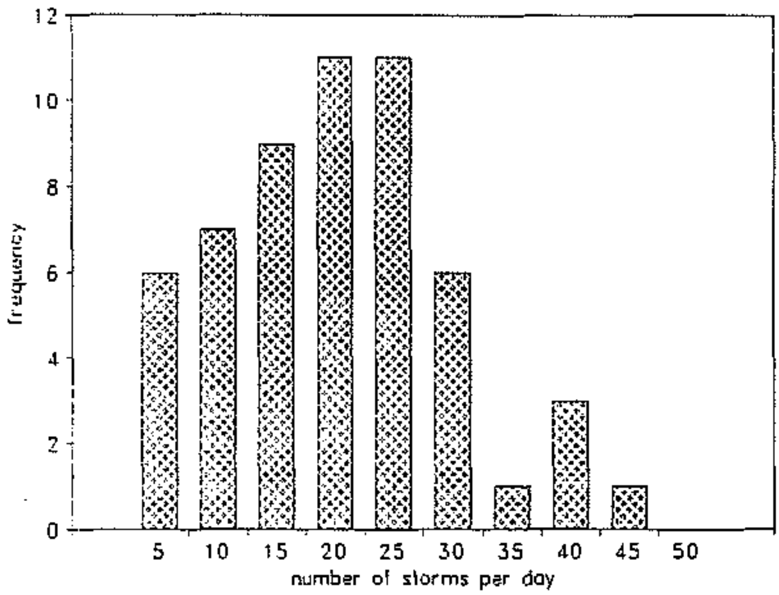

Figure 6 Frequency distribution of the number of seedable storms that develop during a day in the Bethlehem and Carolina areas

Part 2
Modelling

CHAPTER 6

METHODOLOGY ADOPTED FOR THE SIMULATION OF A WEATHER MODIFICATION OPERATION

My own navigational technique is to find a car, or the nearest equivalent, which looks as if it knows where it is going and follow it. I rarely end up where I was intending to go, but often I end up somewhere that I needed to be.

Dirk Gently, in The Long Dark Tea-time of the Soul. Douglas Adams

The results from the analysis of the radar data showed that the effect of cloud seeding on the mean areal daily rainfall, expressed as a percentage of the natural mean areal rainfall, is independent of the mean areal rainfall. Furthermore, this effect can be modelled as a random variable drawn from a lognormal distribution. These two results greatly simplify the approach needed to model the effect of an operational weather modification programme. This Chapter will introduce the models used to generate the weather modification effect and to stochastically generate new sequences of rainfall data. Chapter 7 deals with the generation of the rainfall maps, and finally the implementation of the models is discussed in Chapter 8.

6.1 Model for the effect of weather modification

The models developed for the study area should be portable to other study areas within the region reaching from Bethlehem to Nelspruit. The radar data, as discussed before, represents a fragmented record of the rainfall in three areas within this corridor, and therefore cannot be used as a basis for generating spatially distributed daily rainfall maps. This leaves the daily rain gauge network operated by the Weather Bureau as the only feasible source of rainfall data. The objective then is to develop a suite of models that use daily rain gauge data as input to generate sequences of maps representing spatially distributed daily rain fields of "natural" and "modified" rainfall. The simulation of a weather modification programme based on historical radar data has shown that the effect, expressed as a fraction of the mean areal daily rainfall, appears to be independent of the mean areal daily rainfall. It is not useful to examine the dependence of the seeding effect on more subtle rain field characteristics since interpolation from rain gauge measurements yields such a coarse representation of the true rain field. The effect of cloud seeding will be modelled as a lognormal distribution with parameters that are independent of the rain field characteristics, except that only scattered rain days are modified.

The model used to simulate a weather modification programme using historical data is as follows:

1) Generate a sequence of historical daily rain fields using rain gauge data.
2) Classify the rain fields into dry, scattered, and general rain days.

3) Generate a seeding effect for each scattered rain day.
4) Modify the seedable rain day by the seeding effect and insert into the modified rainfall data base.

6.2 Rain day model

A further requirement of the end-user studies is that it must be possible by using an appropriate model to stochastically generate new sequences of spatially distributed rain fields, and impose a modification effect onto these synthetic data. This rain day model was developed by Prof. G.G.S. Pegram, whose assistance is gratefully acknowledged. Mesoscale climate is assumed to be fundamentally a switching type process which enables shifts between distinctive rain day states. This is in contrast to the continuous type of variable which could be modelled by an autoregressive moving average model (ARMA). An obvious model for such states is a Markov-chain possibly incorporating a multiple lag structure. This is easily modelled once the states have been defined and measured. The dependence within the climate model alone is assumed to be sufficient to maintain the general dependence structure of the rainfall process over the study area. This simplifying assumption is made at this stage because it is only the scattered rainfall days which are seedable, and the structure of a scattered rain field does not appear to have a carry-over effect to the following day. Even general rain days do not often occur in sequences longer than three days.

If it is assumed that the fundamental difference between a wet year and a dry year is the increased frequency of general rain days, and not any characteristic of the rain days themselves, for example higher mean areal rainfall per rain day during a wet year, then it should be possible to reconstruct a rainfall record by sampling at random from historical rain days of the appropriate type. The characteristics of general rain days are assumed to be dependent on the number of consecutive general rain days. This appears to be a reasonable assumption since the very large scale events would cause wide spread rain over a number of days, and tend to produce more rainfall per day than the one-day events.

To verify this assumption Weather Bureau daily rainfall data for a square 200km on a side centred on Carolina was used to classify a 30-year sequence of daily rainfall into the three rain-day states. The mean areal rainfall for each day within a one-day, two-day, three-day and four-day sequence of general rain days was calculated. Table 9 shows the mean, standard deviation and number of rain days in each of the four data sets. Figure 7 plots the probability that the mean areal rainfall is equalled or exceeded. From Table 9 it can be seen that the one-day case has the lowest mean rainfall, and the four-day case has the highest mean rainfall. The major difference however between the one-day case and the multi-day cases is the increased standard deviation, pointing to the fact that the extreme one-day events are more likely to be found within multi-day general rainfall events. This conclusion is supported by Figure 7 where the increased probability of extreme events may be seen in the fatter tail observed for the multi-day events.

Table 9 Mean daily areal mean rainfall, standard deviation and number of rain-days for the one-day, two-day, three-day, and four-day general rain day sequences.

	mean (mm)	standard deviation (mm)	number of days
one-day	11.3	4.1	236
two-day	12.7	7.1	196
three-day	12.9	5.0	84
four-day	14.0	7.1	80

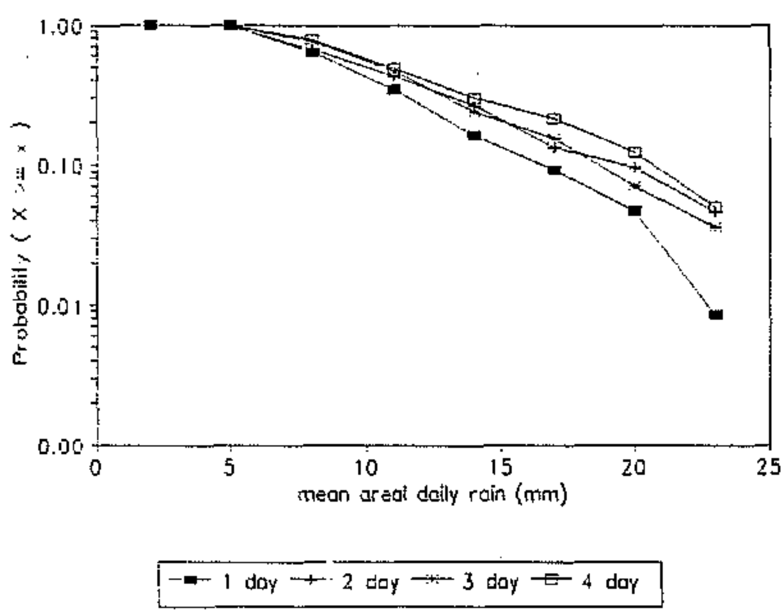

Figure 7 Accumulative probability distributions of the mean areal daily rainfall for sequences of consecutive general rainfall

The transition probabilities between the three rain day states were calculated and are found in Table 10. From this table it can be seen that a dry day is likely to follow a dry day, and a scattered rain day is likely to follow either a scattered or a general rain day.

The stochastic model will therefore be used to generate a climate sequence, an historical rain day will be selected at random from a library of scattered, one-day, two-day, three-day and four-day general rain days and assigned to that day.

The model used to stochastically generate sequences of spatially distributed rain fields

is as follows:
1) Generate a sequence of historical daily rain fields using rain gauge data.
2) Classify the rain fields into dry, scattered, and general rain days.
3) Calculate the transition probabilities between these three states.
4) Use a Markov chain model to generate new sequences of dry, scattered, and general rain days.
5) Build a new data set with this new sequence of climate states, selecting the appropriate days at random from the historical record.
6) Modify this synthetic data set as before.

Table 10 Transition probabilites for the three-state rain day model

	dry	scattered	general
dry followed by a	0.583	0.406	0.001
scattered followed by a	0.103	0.801	0.096
general followed by a	0.007	0.624	0.369

CHAPTER 7

GENERATION OF DAILY RAINFALL MAPS

The new improved Monk Plus models were twice as powerful, had an entirely new multi-tasking Negative Capability feature, were twice as fast and at least three times as glib.

Electric Monk Plus, in Dirk Gently's Holistic Detective Agency, Douglas Adams

7.1 Introduction

The generation of a large number of daily rain fields using gauge data is a computationally intensive process requiring a fast interpolation algorithm, coupled with an appropriate rain gauge data base. Methods to interpolate rain gauge measurements onto a regular grid are well established for monthly and longer accumulations. Typical applications include interpolating median monthly and annual rainfall values (Dent, 1989). Methods used include various distance weighting schemes (Ripley, 1980), multi-quadric surfaces (Adamson, 1978), optimal interpolation (Bras and Rodríguez-Iturbe, 1985) and regression techniques (Dent et al, 1989). Methods to interpolate daily rain fields are less well established. Shäfer (1991) assumed that the daily rainfall amount reflects trends similar to those found in the median monthly rain fields. This may be true in areas of significant orographic rainfall but is unlikely where convective development is the main meteorological process causing summer rain. An analysis of the over 10 000 convective storm tracks in the Nelspruit area led SWA and CIC (1986) to state:

The point that we want to emphasize here is that not one of these analyses showed a systematic grouping of storm track properties that could be related to the underlying topography. Thus, while echo frequency and direction of movement can be closely tied to terrain, radar-measured storm characteristics cannot. This implies that the underlying topography would influence the rainfall at a point by influencing the frequency of rain days at that point, and not necessarily the spatial distribution of the rainfall on a particular rain day.

A major consideration in the selection of an interpolation algorithm is speed, implying that only the simplest of methods will be investigated. Inverse distance weighting schemes were selected for further investigation. Methods of identifying the gauges that contribute to the rainfall at an ungauged point are to use all the gauges in the study area, to select the gauges within some distance of the point, and to select the nearest gauges to the point, say the five nearest neighbours.

Studies by Doneaud et al. (1981, 1984), Rosenfeld et al. (1990) and Seed and Austin (1990) have shown that the raining area, combined with a climatological mean rain rate, is able to explain up to 98% of the variance of the mean areal rainfall. Since daily rain fields are so intermittent, with extreme gradients within the raining areas which typically cover only a small fraction of the total area, it will be unduly optimistic to expect an interpolation scheme to provide accurate estimates of rainfall at ungauged locations in the rain field. In the light of the fact that the raining area contains most of the variance in the mean areal rainfall, it would be instructive to examine the success of an interpolation scheme in correctly assigning rainfall to a pixel within the rain field. This chapter will therefore examine the effect of increasing the number of nearest neighbouring gauges used in the inverse distance squared weighting scheme on the probability that a pixel in the rain field is correctly assigned rainfall. Thereafter, a fast interpolation algorithm is developed for this project.

7.2 Method

The radar rainfall data from the Carolina radar were accumulated to form maps of daily rainfall and were used as "truth" in this study. The study area has a network of 220 daily rain gauges, approximately 100 km^2 per gauge. The radar derived daily rainfall maps were therefore sampled at the locations of these gauges and used to build a "rain gauge" data set. Figures 8 and 9 shows the area with more than 1 mm of rainfall measured by the radar superimposed on the resulting gauge derived rainfall map for a typical scattered rain day. An inverse distance squared interpolation scheme using 5 nearest gauges was used to interpolate between the gauge values. It is apparent from this Figure that the radar based rainfall maps contain great detail which the gauge derived rainfall map is simply unable to represent. In Figure 9 two large storms have been completely missed by the gauge network.

The fraction of a rain field with a rainfall above a certain threshold is dependent on the value of the threshold (Rosenfeld et al. 1990). Furthermore, it is to be expected that the rain field interpolated from the gauge data will by virtue of the interpolation technique also contain a large area where the rainfall is very close to zero. The results from this study will therefore be dependent on the threshold chosen to delineate the rain / no rain classes. In this study, a pixel was classified as "rain" if the rainfall exceeded 1mm.

The gauge-derived rain / no rain maps were then compared with the radar-derived "truth" to determine the accuracy with which the various interpolation techniques delineate raining areas. There are several measures of classification accuracy used in the field of remote sensing to evaluate the efficacy of a classification scheme in the delineation of various land-cover classes. However, as Drake et al (1987) point out, no single measure has been developed that adequately describes the merits of a given classification. This study will use two measures to describe different aspects of the accuracy of the various methods viz.

a) The ratio of the number of rain pixels in the interpolated rain field divided by the number of rain pixels in the measured rain field (Ra).This will give an indication of any systematic bias in the delineation of the raining areas.

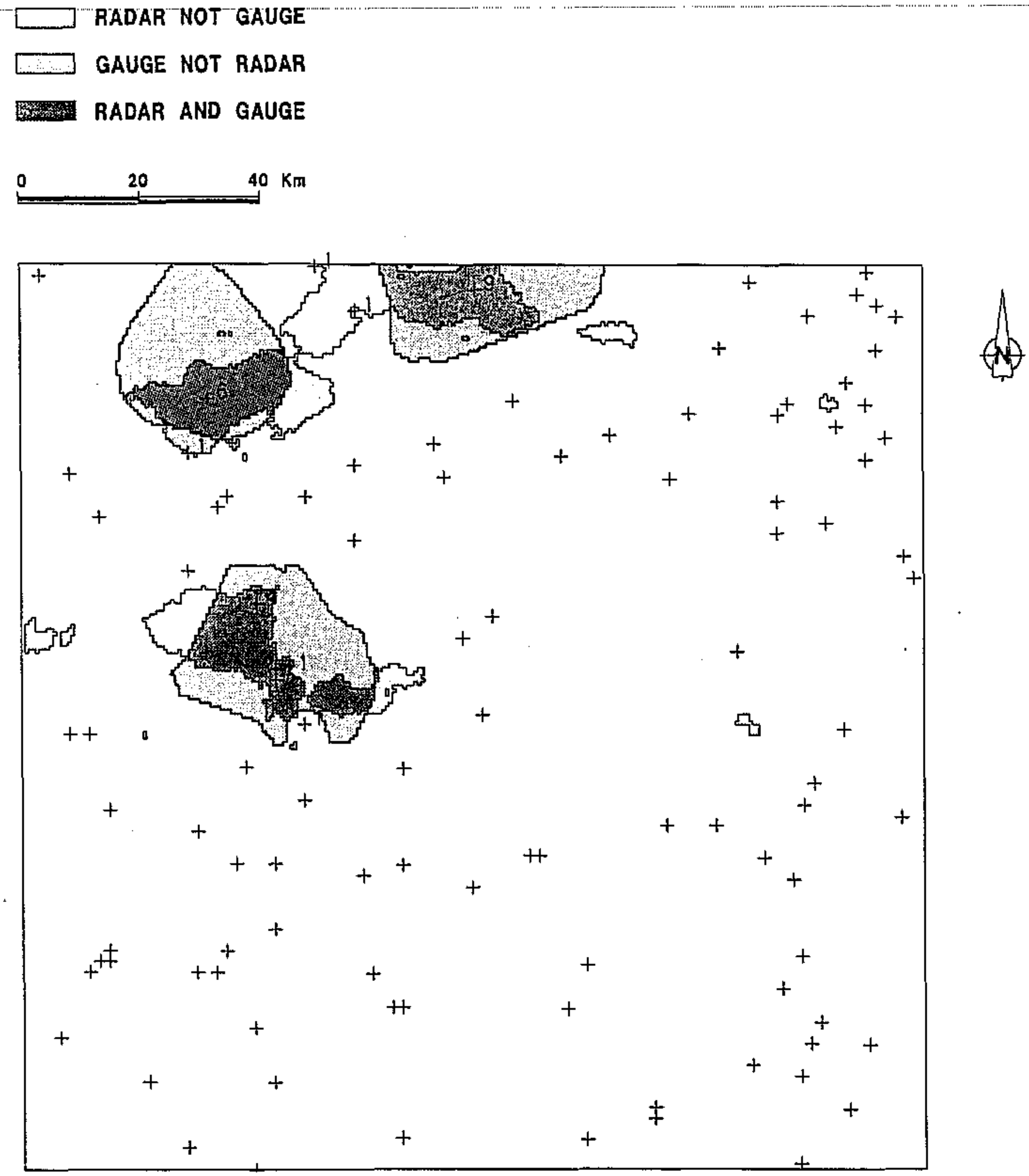

Figure 8 Interpolated and measured rain fields for 28-Jan-1990, + represents the location of a rain gauge.

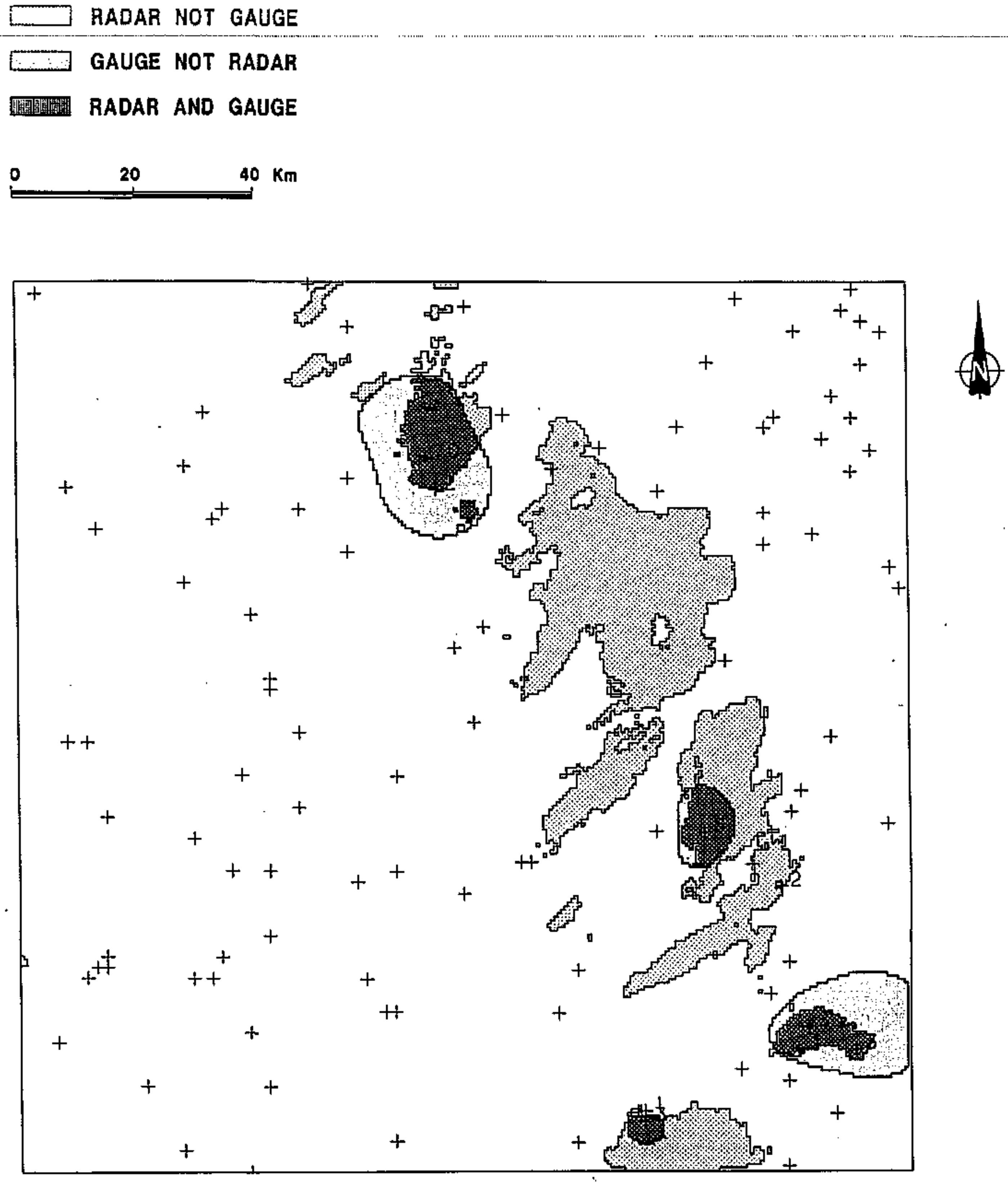

Figure 9 Interpolated and measured rain fields for 3-Nov-1990, + represents the location of a rain gauge.

b) The Jaccard Coefficient J (Sneath and Sokal, 1973), a measure of association, is defined as

$$J = \frac{P}{P+O+C}$$

where
P = the number of pixels correctly classified
O = the number of pixels that were measured as a class, but not classified, and
C = the number of pixels that were classified as a class, but not measured.

The Jaccard Coefficient gives the fraction of overlap between the radar derived rain area, and the rain area derived from the interpolation method.

7.3 Results

The accuracy of the interpolation scheme is dependent on both the interpolation scheme and the characteristics of the rain field. Figure 10 shows the relationship between Ra and the fraction of the study area measuring rain for the various interpolation schemes. The estimated rain area increases as the number of rain gauges used by the interpolation scheme increases. The interpolation scheme using only the nearest gauge tends to under-estimate the rain area for days with a low rain area, whereas the rain area is over-estimated by the schemes using more than one gauge when the rain covers between 20% and 50% of the study area. Figure 11 shows histograms of Ra for the three interpolation methods. The nearest neighbour method is less likely to make large over-estimation errors, however, the bias towards under-estimation is quite evident.

A plot of the Jaccard coefficients for the three interpolation methods is plotted against raining area in Figure 12. From this figure it is evident that the accuracy of the interpolation methods improved as the rain area increased. This could be largely fortuitous since the probability of correctly classifying a raining pixel increases as the raining area increases. Methods using more than one neighbouring gauge do not have more skill in delineating the raining areas than does the nearest gauge method. The rain gauge network showed very little skill in delineating the raining pixels when the rain fraction was less than 0.2 with less than half the pixels being assigned to the correct class.

7.4 Discussion

The validity of any interpolation scheme has to be seen against the extreme variability in rain fields accumulated over short periods. The observed existence of extreme gradients and a generally discontinuous behaviour with rain falling over a small fraction of the area, leads to the conclusion that any interpolation technique based on a sparse set of point measurements will not show great skill in reproducing the measured rain field in these situations. The results of this investigation show that a network of one rain gauge per 100 km^2 is unable to reproduce even the rain / no rain classification with any confidence on days of isolated and scattered convective storms.

From Figure 12 it can be seen that the skill of a distance weighting technique to correctly classify the image into the rain / no-rain classes is more sensitive to the raining area than the number of nearest neighbours used for the interpolation scheme. Other criteria will therefore have to be used to select the best interpolation method. The technique based on a single gauge under estimates the rain area on days with isolated rain, however, this method does not tend to over estimate on days with more

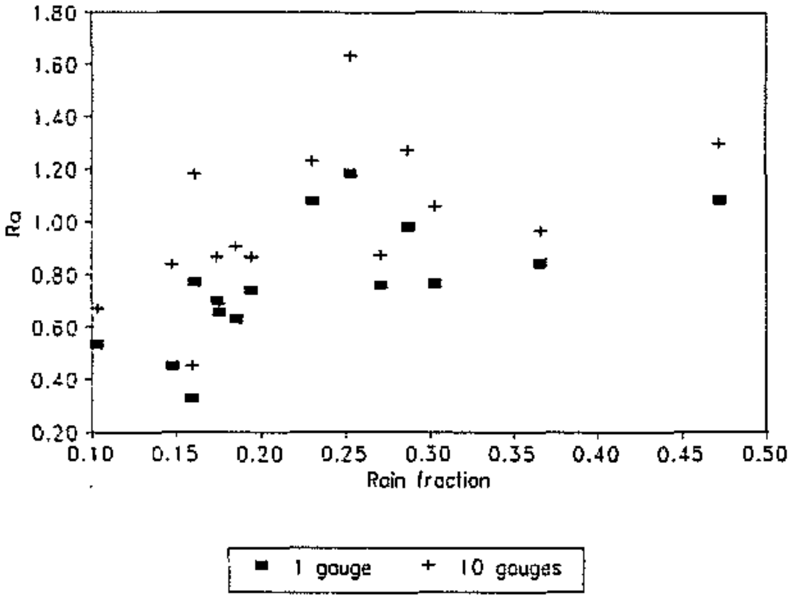

Figure 10 The ratio of the interpolated rain area and the measured rain area (Ra) plotted against the measured rain area

wide spread rain, which are hydrologically more significant than the isolated rain days.

The Thiessen interpolation method (Thiessen 1911) assigns the rainfall measured at the nearest rain gauge to the point of interpolation, however, this method does not reproduce the gradients that are known to exist in rain fields. An alternative approach is to adopt a hierarchical technique, whereby the first step is to use the nearest gauge to classify the pixel into the rain / no rain classes, and thereafter use a distance weighting scheme to estimate the rainfall depth if the pixel is assigned the rain class. The advantage of this approach is that the rain area is not over estimated when the rain field is more wide spread, while at the same time making use of the correlations that are known to exist between rain gauges to produce gradients in the rain field.

The results of this study show that the accuracy with which a rain gauge network can reproduce a rain field is largely determined by the characteristics of the network and the rain field sampled by the rain gauges, rather than the algorithm used for interpolating between the point measurements. If the gauge network is relatively sparse, and the rain field covers only a small fraction of the study area, then the network will be unable to reproduce even the rain / no-rain areas with skill, even if mathematically complex methods are used to interpolate between the gauges. On the other hand, even simple interpolation methods will give reasonable results if the gauge network is dense or the rain field is widespread.

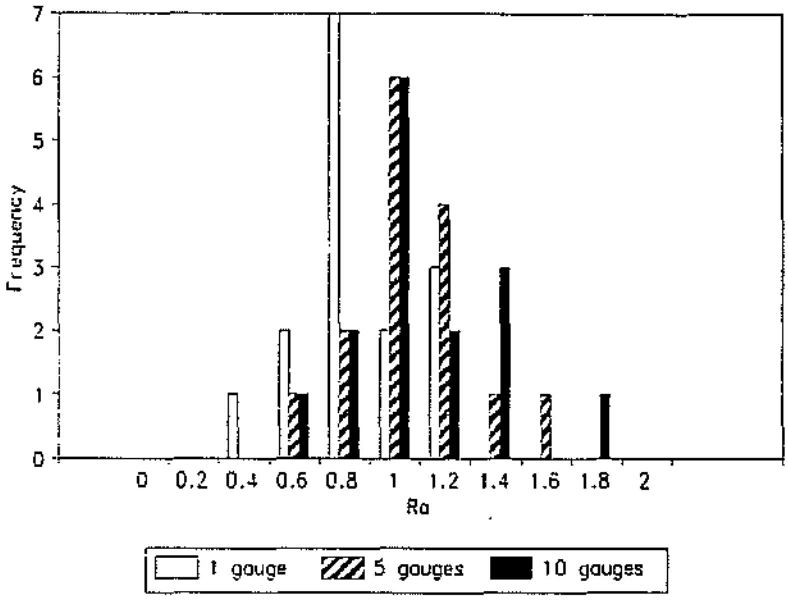

Figure 11 The frequency distribution of the ratio of the interpolated rain area over the measured rain area (Ra)

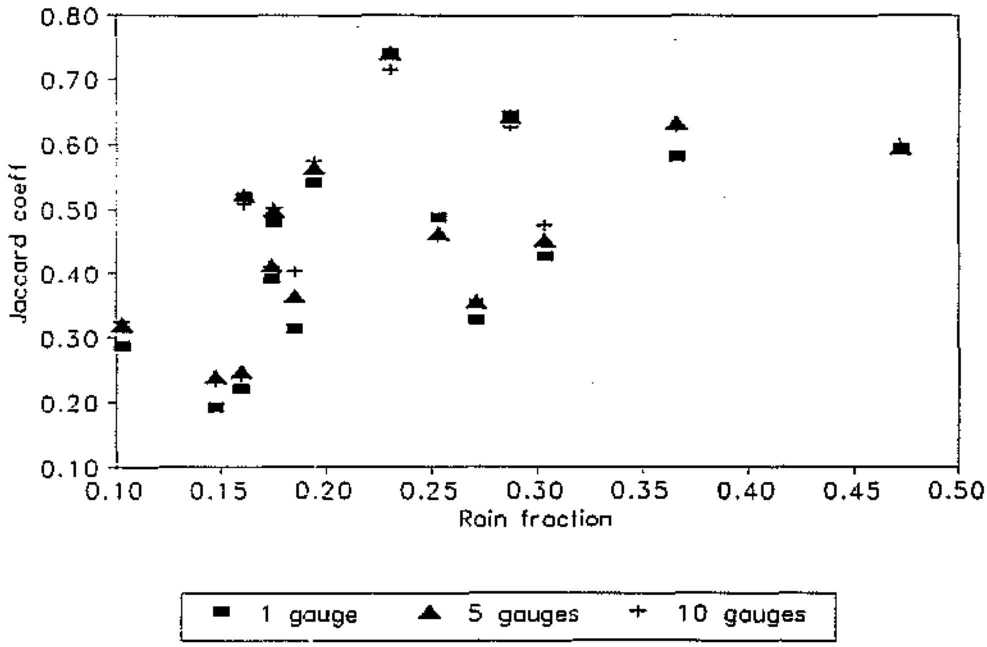

Figure 12 The Jaccard Coefficient plotted against the rain area

7.5 A fast algorithm for inverse distance squared interpolation

Interpolation by means of a distance weighting scheme using a few of the nearest rain gauges requires that the local rain gauges are identified at each pixel in the map. This is an expensive operation since all the gauges in the study area must first be ranked by increasing distance at each pixel. However, neighbouring pixels will most likely make use of the same interpolating gauges, with the weights assigned to each gauge differing somewhat. One way to reduce the number of searches required to produce a map therefore, is to divide the map into local neighbourhoods or tiles, say squares three pixels on a side, and to rank the rain gauges according to increasing distance from the centre of each tile. The same set of nearest gauges is then used for the nine pixels within the tile, the weight for each gauge is recalculated at each pixel. A further time saving can be made by assuming that the entire tile has zero rain if the gauge closest to the centre of the tile has zero rain. The average time taken for this method to generate a 256 line by 256 sample image using 220 rain gauges 11% of the time taken by a standard distance weighting method to generate the same image.

CHAPTER 8

SIMULATION OF A WEATHER MODIFICATION PROGRAMME

It claimed to produce the widest possible range of drinks personally matched to the tastes and metabolism of whoever cared to use it. When put to the test, however, it invariably produced a plastic cup with a liquid which was almost, but not quite, entirely unlike tea.

Nutri-Matic Drinks Synthesizer, in The Restaurant at the End of the Universe. Douglas Adams.

This Chapter uses the Weather Bureau daily rainfall data in the test area to construct daily rainfall maps for a 30-year period. Thereafter an operational weather modification programme is simulated and the results discussed. Finally, the stochastic model to generate new sequences of daily rainfall for the area is verified.

8.1 The generation of a rainfall data base for the Carolina study area

The Weather Bureau has records from some 230 rain gauges within 100 km of the Carolina radar. Rainfall data covering the period 1960 to 1989 were obtained from the Weather Bureau. The spatial resolution of the rainfall maps was set somewhat arbitrarily at 2 km, as this is considered to be a reasonable resolution for daily rainfall maps derived from rain gauge data. The north west corner of the map area was set at 25^{o} 15' S, 29^{o} 15' E. The map area was a square 200km on a side.

The length of the record required by the various impact studies has not been clearly defined as yet. However, a period of 30 years seems to be a reasonable first estimate. Since there will be approximately 200 daily rainfall maps per year, the data handling problems are expected to become severe for data sets much longer than 30 years. The daily rainfall maps for the study area were generated and used as input into a simulation of an operational weather modification programme.

The probability distribution of Table 8(b) for a daylight hours only seeding operation was used to generate a sequence of modified rainfall based on the historical record from 1-Oct-1960 to 1-Oct-1970. The total rainfall measured over the period was calculated to be 6047mm compared with 6490mm for the modified data set, representing an increase of 7.3% in the mean annual rainfall. It is interesting to note that Görgens and Rooseboom (1990) thought that the annual effect of weather modification was likely to lie within the 4% to 10% range.

8.2 Stochastic generation of new rainfall series

Twelve sequences of daily rainfall of 30-years duration were generated using the climate model. Tables 11, 12, and 13 compare some of the characteristics of the historical data with the synthetic data sets and Figure 13 shows the mean daily rainfall for the measured and synthetic data sets. Figure 14 compares the relative frequency of the total summer rainfall for the historical record with the summer rainfall totals in the synthetic rainfall. Figures 15 and 16 show the relative frequency of the number of scattered and general rain days in the synthetic and historical data sets respectively. From Table 11 and Figure 14 it can be seen that the model is able to reproduce the probability distributions of the summer rainfall totals although the intra-seasonal variability is not adequately reproduced. The frequency distributions for the number of scattered and general rain days per summer are also preserved. The climate model is therefore able to generate new sequences of daily rainfall that have sufficient verisimilitude to be used as input for weather modification simulations.

Table 11 A comparison between the total summer rainfall for a 30-year measured rainfall sequence and 12 30-year synthetic rainfall sequences

	25 percentile	median	75 percentile
synthetic	465	519	540
measured	478	540	586

Table 12 A comparison between the mean number of scattered rain days for a 30-year measured rainfall sequence and 12 30-year synthetic rainfall sequences

	mean	standard deviation
synthetic	128	9
measured	130	10

Table 13 A comparison between the mean number of general rain days for a 30-year measured rainfall sequence and 12 30-year synthetic rainfall sequences

	mean	standard deviation
synthetic	20	6
measured	20	5

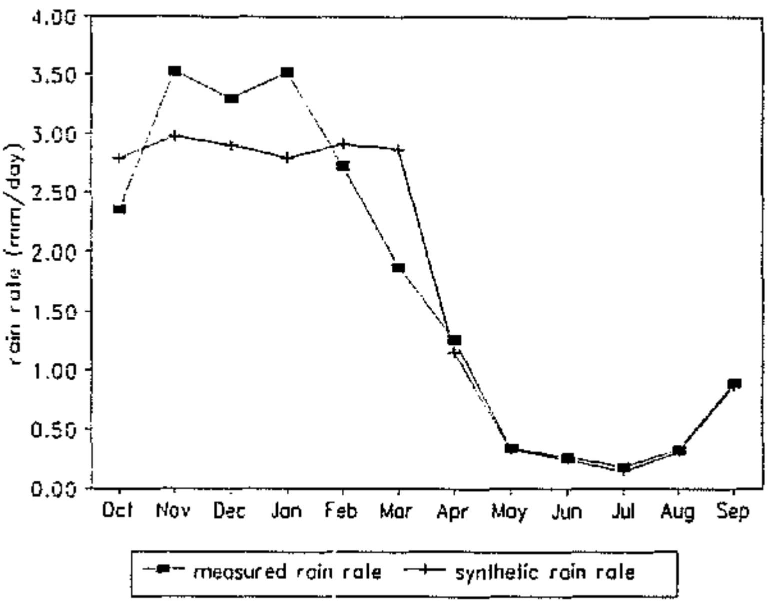

Figure 13 Mean monthly rain rate for the synthetic and measured rainfall series

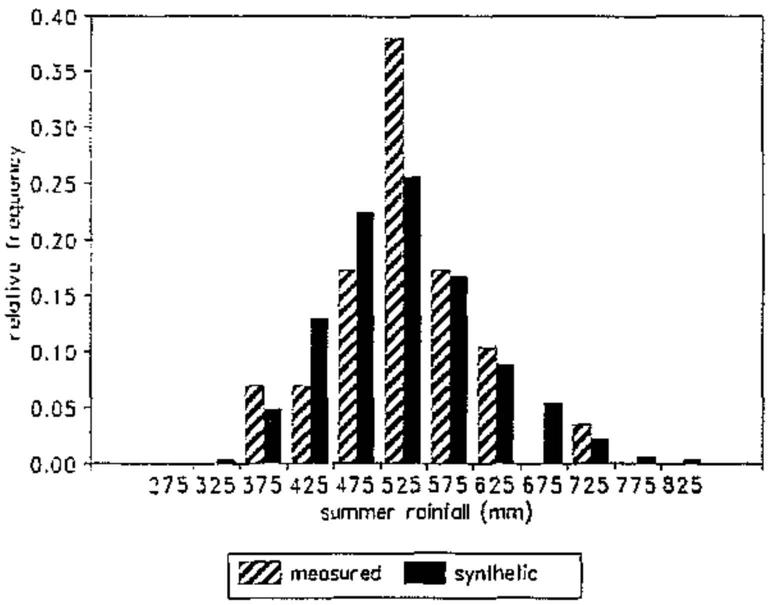

Figure 14 Relative frequency of total summer rainfall for the measured and synthetic data

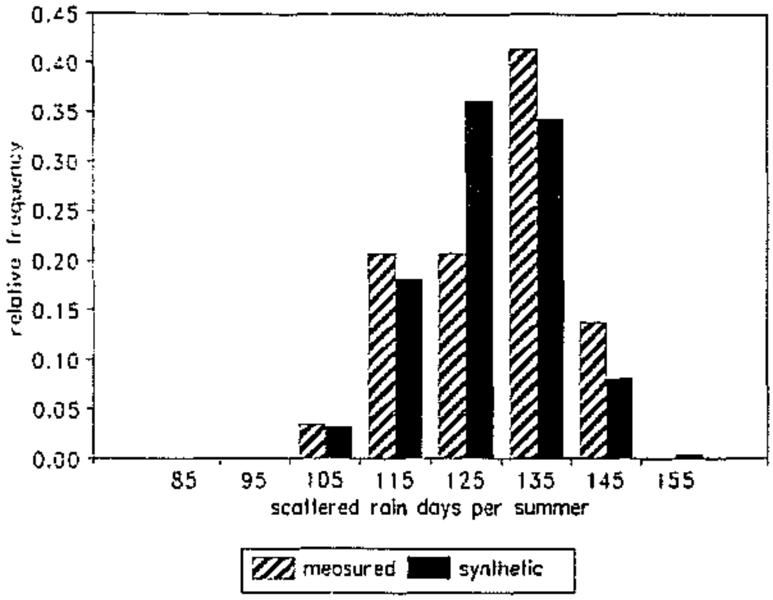

Figure 15 Relative frequency of the number of scattered rain days per summer for the measured and synthetic data

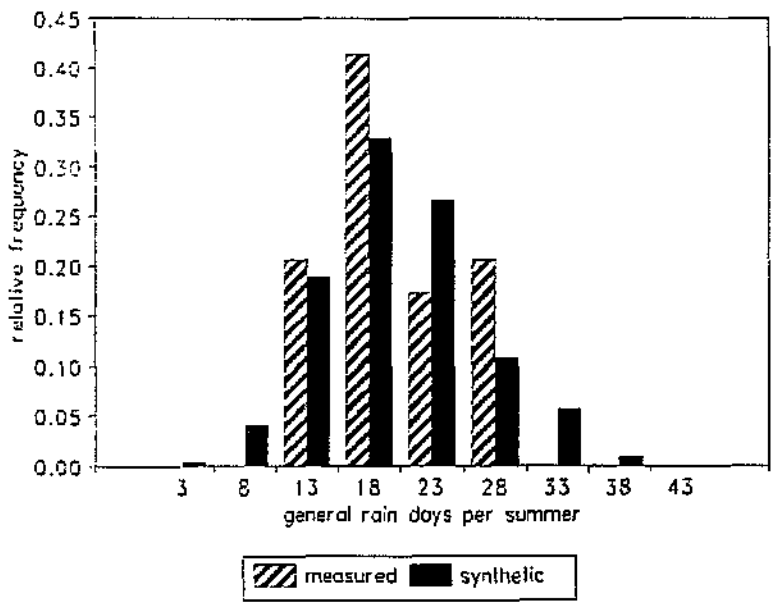

Figure 16 Relative frequency of the number of general rain days per summer for the measured and synthetic data

CHAPTER 9

CONCLUSIONS

'The Answer to the Great Question of Life, the Universe and Everything is Forty-two' said Deep Thought, with infinite majesty and calm.

Deep Thought, the second greatest computer in the Universe of Time and Space on the meaning of Life, the Universe and Everything in: The Hitch Hikers Guide to the Galaxy. Douglas Adams.

This project has been able to convert the seeding effect expressed in terms of storm track properties into an effect expressed as a fraction of mean areal daily rainfall. The effect of weather modification on a day showed great variability, with a number of days where the seeding effect was in excess of 20%. The Bethlehem and Carolina radar data sets turned out to be quite similar in their response to the simulations. The efficiency of the cloud seeding was largely determined by the mean duration of the seedable storms, and related to this was the finding that a 15-minute delay between first echo and cloud treatment has serious consequences to the seeding effect. An operational weather modification programme will therefore need careful planning and real-time storm tracking capabilities at the radar site.

The weather modification effect on daily rainfall will be almost unmeasurable, even with a well calibrated radar, except on a few highly successful days. The issue of how to verify a successful weather modification experiment with ground based rainfall measurements needs far more attention, in particular, relocation of the Bethlehem radar and acquisition of better radar hardware need to be considered.

The historical radar data at my disposal was barely adequate for a project of this type, this after more than 20 years of weather modification research. The effect of weather modification was modelled in terms of mean areal rainfall, however, there are good reasons to expect important spatial variability in the number of seedable storms and the seeding effect at smaller scales. These issues can only be addressed in a systematic manner once 24-hour radar coverage becomes available, particularly in the Carolina area.The cloud seeding simulations were based on the most probable seeding effect stated by Görgens and Rooseboom (1990). No attempt was made to model variability in the seeding effect from one storm to another, or within the time series of the effect. However, the models used to simulate the weather modification are such that a new, or variable, seeding effect can easily be accommodated once more is known about the distribution of the seeding effect at that scale.

A simple stochastic model to re-randomize daily rainfall has been successfully developed. The model is novel and makes possible for the first time the simultaneous stochastic generation of daily rainfall at a large number of sites within an area. At present, the model has been developed to model summer rainfall only, and does not adequately model the differences between the months of the summer. In particular, the October month is the driest summer month in that area, which is not reflected by the model.

Major spin-offs from this project include the development of a fast rainfall interpolation algorithm together with a database management system capable of managing 6000 rain maps within a single base. A substantial package for processing and managing radar data was developed during the course of the project and has already been installed at the Bethlehem radar.

CHAPTER 10

REFERENCES

Adamson, P.T. 1978. The analysis of areal rainfall using multiquadric surfaces.Technical Report No. TR82. DWAF, Pretoria, RSA.

Alexander, W.J.R., 1982. Notes on the development of unconventional water resources in South Africa, with particular reference to rainfall enhancement. Internal Report, DWAF.

Bras, R.L., and I. Rodríguez-Iturbe, 1985. Random functions and hydrology. Addison-Wesley Publishing Company.

Chow, V.T., D.R. Maidment, and L.W. Mays, 1988. Applied Hydrology. McGraw-Hill Book Company, New York.

Court, A.P., 1979. Rainfall characteristics of classification systems used by the BEWMEX project. Progress Report No. 14, S.A. Weather Bureau, Department of Environment Affairs, Pretoria, South Africa.

Daniel, W.W., 1978. Applied Nonparametric Statistics. Houghton Mifflin Company,Boston.

Dent, M.C., S.D. Lynch, and R.E. Schulze, 1989. Mapping mean annual and other rainfall statistics over southern Africa. Dept. Ag. Eng., University of Natal, Pietermaritzburg, RSA. ACRU Report No. 26.

Drake N.A., J.J. Settle, J.R. Hardy, and J.R.G. Townshend, 1987. The development of improved algorithms for image processing and classification. Final report of NERC Special Topic GST/02/129. Natural Environment Research Council, UK.

Doneaud, A.A., P.L. Smith, A.S. Dennis, and S. Sengupta, 1981. A simple method for estimating convective rain volume over an area. Water Resour. Res.,17, 1676-1682.

Doneaud, A.A., S.I. Niscov, D.L. Priegnitz, and P.L. Smith, 1984. The area-time integral as an indicator for convective rain volumes. J. Clim. Appl. Meteorol., 23, 555-561.

Terreblanche, D., 1992. NPRP Scientist, Bethlehem Weather Bureau - personal communication.

Ematek (CSIR) and Cloudquest (Pty) Ltd, 1990. Programme for atmospheric water supply (PAWS) Phase 2: 1987 - 1989. Report to the Water Research Commission, Pretoria, South Africa. WRC Report No. 133/5/90.

Görgens, A.M., and A.Rooseboom, 1990. Potential impacts of rainfall stimulation in South Africa: A planning study. Water Research Commission, Pretoria, South Africa.

Grosh, R., 1989. 1987/1988 PAWS Report, Ematek, CSIR, Pretoria.

Harrison, M.S.J., Hudak, D.R., Lyons, J.H., Murino, G., Shaw, W.S., and P.C.L. Steyn, 1978. BEWMEX Progress Report No 6, Weather Bureau, Dept.Environment, Pretoria.

Hodson, M., 1989. 1978/1988 PAWS Report, Ematek, CSIR, Pretoria.

Katsiambirpas, E.E, and E.J. De Jager, 1981. Rainfall in the BEWMEX area. Progress Report No 22. S.A. Weather Bureau, Dept. Environment, Pretoria.

Maaren, H., 1984. Run-off augmentation and weather types: Practical implications. In: H. Maaren (Ed.). First South African National Hydrological Symposium. Technical Report No 119, DWAF, P. Bag X313,Pretoria, South Africa.

Mather, G. 1991. NPRP Scientist, CloudQuest, Nelspruit - personal communication.

Mason-Williams, S., 1984. The Bethlehem Run-off Augmentation Research project:Past, Present, and Future. Technical Report No 118, DWAF, P. Bag X313, Pretoria, South Africa.

Ripley, B., 1980. Spatial Statistics. John Wiley and Sons, London, 44-75.

Rosenfeld, D, D. Atlas, and D.A. Short, 1990. The estimation of convective rainfall by area integrals 2. The height-area rainfall threshold (HART) method. J. Geophys. Res. Vol. 95(D3), 2161-2176.

Seed, A.W. and G.L. Austin, 1990. Variability of summer Florida rainfall and its significance for the estimation of rainfall by gauges, radar, and satellite. J. Geophys. Res. Vol. 95(D3), 2207-2215.

Simpson Weather Associates and Cansas International Corporation, 1986.Programme for Atmospheric Water Supply, Phase 1 1983-1986, Volume 2:Natural Clouds and Rain in Nelspruit. WRC Report No. 133/2/88. Water Research Commission, Pretoria, South Africa.

Shäfer, N.W., 1991. Modelling the areal distribution of daily rainfall.Unpublished MSc thesis, Dept. Ag. Eng., University of Natal,Pietermaritzburg.

Sneath, P.H.A., and Sokal, R.R., 1973. Numerical Taxonomy. Freeman, San Francisco.

Steyn, P., and R. Bruintjies, 1990. A convective cloud climatology for the Bethlehem area.

Tabios, G.Q., And T.D. Salas, 1985. A comparative analysis of techniques for spatial interpolation of precipitation. Water Resour. Bul., 21(3),365-380.

Thiessen, A.H., 1911. Precipitation averages for large areas. Monthly Weather Review, July 1911, 1082-1084.