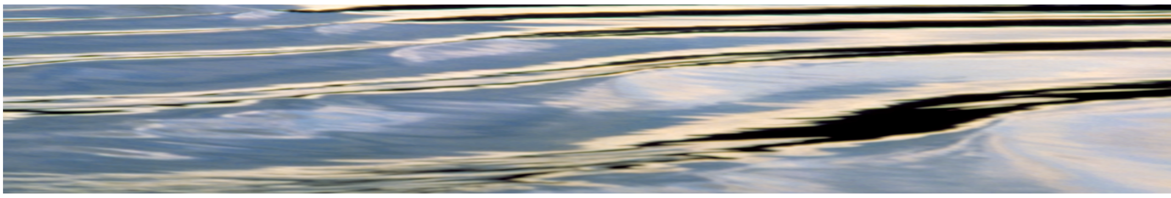
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

ON THE CALIBRATION OF AUSTRALIAN WEATHER RADARS

TECHNICAL REPORT
Report **02/7**
September 2002

Alan Seed / Lionel Siriwardena / Xudong Sun / Phillip Jordan / Jim Elliott



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Preface

Weather radar offers an enormous potential to improve the quality of rainfall measurement. This potential can translate into benefits in many sectors of the water industry ranging from improved design information, decisions on water allocation and management, through to improved weather and flood forecasts for greater public safety. A key step in transforming weather radar observations into accurate rainfall estimates however is the calibration of the weather radar data. This involves converting the quantity actually observed by the radar (known as reflectivity) into an estimate of rainfall intensity. The current approach used widely with Australian weather radars is to rely on a set of calibration factors that represent average, or climatological, conditions. This can lead to quite large errors in rainfall estimates.

This report describes investigations to improve the calibration process for weather radars in Melbourne, Sydney and Darwin. Raingauge data has been used to analyse the likely errors in rainfall estimates from radar and calibration strategies to improve the quality of the radar rainfall estimates are proposed.

Francis Chiew
Program Leader
Climate Variability Program

Executive Summary

Weather radar can be used to measure rainfall with high spatial and temporal resolution. The radar measurement process involves the transmission of a beam of electromagnetic radiation from a radar transmitter and the measurement of the amount of radiation backscattered from the rain back to the radar receiver, normally co-located with the transmitter. This reflected radiation is known as the reflectivity (Z) which can be shown to be related to rainfall intensity (R) through a power law relationship of the form $Z=aR^b$.

There are two broad classes of error in radar measurement of rainfall; errors that affect the measurement of the returned power and its conversion to reflectivity, and errors that affect the transformation of reflectivity to rainfall intensity. These errors can be controlled to some degree through the selection of appropriate radar hardware and by the way the radar is operated. However, the use of raingauge data to calibrate the parameters of the power law relationship is normally necessary before the data can be used quantitatively. The most basic calibration method is to determine a fixed, or climatological, relationship using a long sequence of radar data together with either raingauge or disdrometer (a device that measures the size distribution of raindrops) measurements. This climatological relationship represents the "average" relationship for the particular climate and radar. The alternative approach is to use a network of raingauges and a statistical technique to adjust the Z-R relationship on an event basis using the co-located gauge and radar data. This approach however is subject to measurement and sampling errors that can be reduced through some spatial and temporal averaging of the data. Both types of calibration were applied in this study.

Archived data from Darwin, Sydney and Melbourne were used to determine the climatological Z-R relationship for the radar located in each of these cities, using between 400 and 600 days of data. The radar reflectivity was converted to rainfall using the standard Z-R relationship for mid-latitude widespread rainfall for Sydney and Melbourne, and a relationship derived previously for Darwin. These 10-minute rainfall fields were then accumulated into daily rainfall totals. Estimates of mean areal daily rainfall were calculated from raingauge data by determining the arithmetic mean of the gauges within 128km of the radar. These two estimates of daily rainfall for each radar were then used to calibrate the multiplicative term a in the Z-R relationship so as to minimise an error measure, while keeping the exponent b in the relationship fixed. The climatological Z-R relationships so determined were shown to have an RMS error of 3-4 mm for daily rainfall accumulations in Sydney and Melbourne and 7-8 mm for Darwin, where the mean rainfall is higher.

Calibration of the Z-R relationship on an event basis (hourly time interval) requires storms of diverse characteristics that originate from different meteorological systems such as thunderstorms and frontal storms. An average Z-R relationship for each event can be established as an appropriate calibration strategy allowing for the variation of parameter values of the Z-R relationship with different types of storms. An investigation of this variation was first undertaken for the Letterbox radar near Sydney. The climatological relationship established in an earlier study was used to calculate 10-minute rainfall intensity fields from the radar reflectivity data, which were then accumulated into 1-hour rainfall fields. Using raingauge data for the area covered by the radar synchronised with the radar data, the multiplicative parameter a in the Z-R relationship was calibrated using two approaches; by equalising storm totals and by minimising the RMS error. While slightly different parameters were obtained, overall the two methods gave very similar results. Testing showed that results of similar quality could be achieved with different values of the exponent b in the relationship and so the pragmatic approach of fixing b according to climate type, as recommended from other studies, was taken. The calibrated values of the multiplicative parameter a varied widely across the seven events tested. An analysis of this variation suggested three possible classifications; convective storms and, within those generally classified as widespread, a separation of those caused by an East Coast low from those with a more westerly offshore wind flow. The coefficient of variation of the spatial distribution of rainfall was used as a measure of the relative variability of the rainfield. This measure was able to classify 70% of the convective cases correctly and 90% of the widespread cases correctly.

Rainfall event calibration was also undertaken for the Melbourne radar by determining the value of the multiplicative parameter a such that the RMS error between gauged rainfalls and averaged hourly radar rainfalls at the same locations was minimised. In general it was found that the Melbourne radar, using these calibrated relationships, can produce estimates of the hourly mean areal rainfall that are within 1 mm per hour of that measured by a relatively dense gauge network. No attempt was made to develop different relationships based on storm type for Melbourne.

It was concluded that a minimum network of 15-20 gauges was needed for effective climatological and event calibration, and 30-50 gauges for hourly on-line calibration.

1. Introduction

1.1 Background

The investigation of space-time characteristics of rainfall requires the preparation of high-resolution maps of historic rainfall events. Weather radar is the best source of high-resolution spatiotemporal rainfall data. However, before these data can be used quantitatively they need to be calibrated against raingauge measurements. This report discusses the work done on weather radar calibration, initially as part of CRC for Catchment Hydrology Project FL2 "Spatial distribution of rainfall and storm movement (using remote sensing)" and as continued in the current CRC Project 5.1 "Modelling and forecasting hydroclimate variables in space and time".

The Australian Bureau of Meteorology has operated a network of weather radars since 1948 when 15 (second-hand) naval radars were purchased for the measurement of upper winds [Cassidy, 1998]. The first Australian radar rainfall scans were taken in Melbourne in 1953 [Brann, 1961] so as to provide rainfall nowcasts for an outdoors function attended by Her Majesty Queen Elizabeth II. The first quantitative estimation of rainfall by radar to be published in Australia was the analysis of a severe storm near Brisbane by Barclay [1964].

Despite over 40 years of operational experience with an extensive network of weather radars, the following quote of Ashton [1963] still has relevance today:

"No discussion of studies on areal rainfall for hydrometeorological purposes is complete without reference to the potential of radar scanning. Application of radar to the problem of estimating area and intensity of rainfall in a series of observations is only at a rudimentary stage in Australia. The potential value is so great, however, that all improvements, as soon as available, should be applied in the field on a continuing basis. Here we have something so obviously useful that neglect of it is unthinkable"

This report provides a brief introduction to radar rainfall measurement and the art of radar calibration by means of a network of raingauges, and then discusses the calibration of the Darwin, Sydney, and Melbourne radars.

1.2 Radar Rainfall Measurement

Radar rainfall measurements are highly susceptible to errors from many sources. This section starts by briefly explaining the process of radar rainfall measurement. Then, based on this understanding of the measurement process, the sources of errors in radar rainfall measurements are discussed.

The following summary of the radar measurement process concentrates on estimation of rainfall intensity by radar, a more complete development is given in Doviak and Zrnic [1984 pp.26-28, 33-34, 51-58].

A radar transmitter emits a beam of electromagnetic radiation. When this beam intercepts an object, a small fraction of the radiation is scattered by the object in other directions. Some of this scattered radiation may be directed toward a receiver, which is normally located at the same position as the transmitter. The amount of radiation backscattered to the receiver depends on the radiation intensity transmitted to the object by the radar and the physical characteristics of the target. The "size" of the target, as seen by the radar, is called its backscatter cross-section, which is usually different from its physical cross-section. The backscatter cross-section of a water droplet, σ_b, is given by:

$$\sigma_b = \frac{\pi^5 |K_w|^2 D^6}{\lambda^4} \qquad \text{Equation 1-1}$$

where $|K_w|$ is the magnitude of the refractive index of water, D is the diameter of the water droplet and λ is the wavelength of the radiation emitted by the radar.

The sum of the sixth powers of the drop diameters per unit volume (V),

$$Z = \sum D^6 / V \qquad \text{Equation 1-2}$$

is known as the reflectivity, Z, and the received power, Pr, from a unit volume filled with raindrops at distance r from the radar can be shown to be

$$\Pr \propto \frac{Z}{r^2} \qquad \text{Equation 1-3}$$

Reflectivity, Z, is expressed in units of mm^6/m^3. Reflectivity commonly varies across six orders of magnitude. It is therefore usually more convenient to express Z in decibel units

$$dBZ = 10\log_{10} Z \qquad \text{Equation 1-4}$$

Marshall and Palmer (1948) showed that the distribution of the number versus the diameter for raindrops can be expressed as:

$$N_D = N_0 e^{-\Lambda D} \qquad \text{Equation 1-5}$$

where D is the diameter, N_D is the number of drops of diameter between D and $D+\delta D$ in a unit volume, N_0 is a constant, and

$$\Lambda = 41R^{-0.21} \text{ cm}^{-1} \qquad \text{Equation 1-6}$$

Radar reflectivity can therefore be expressed as

$$Z = \int_0^\infty N_0 e^{-\Lambda D} D^6 dD \qquad \text{Equation 1-7}$$

Rainfall intensity can be calculated if the number, volume, and fall speed of raindrops in a unit volume are known. Therefore

$$R = \int_0^\infty N_0 e^{-\Lambda D} \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 v(D)dD \qquad \text{Equation 1-8}$$

The terminal velocity of a drop in still air as a function of diameter, $v(D)$, can be approximated by a power law, and therefore there is a power law relationship between Z and R

$$Z = aR^b \qquad \text{Equation 1-9}$$

which can be estimated empirically using measurements of Z and R, or derived from a parameterisation of the drop size distribution.

1.3 Radar rainfall measurement errors

This section on radar rainfall measurement errors was taken from Jordan [2000].

There are two broad classes of errors in radar measurement of rainfall:

- Errors that affect the measurement of the returned power and its conversion to reflectivity; and
- Errors that affect the transformation of reflectivity to rainfall intensity.

There are seven sources of error that affect the measurement of reflectivity, and two sources of error that affect its conversion to rainfall intensity. The two sections that follow will discuss the nine error sources within these two classes in more detail.

1.3.1 Reflectivity measurement errors

1.3.1.1 Temporal sampling error

Meteorological radars observe a volume of the atmosphere by rotating the antenna in azimuth while tilting the antenna vertically so as to sample the atmosphere as a series of cones. This pattern of antenna scanning is commonly called a volume scan. The rate at which a radar rotates about its axis, and the number of elevation angles used in one volume scan cycle fixes the time between successive scans of the same position in space by that radar. This time difference represents the temporal resolution of the radar.

The movement and development of the rainfall field at time scales shorter than the temporal resolution of the radar therefore produces a measurement error. Fabry *et al*. [1994] used 1 hour of radar data with a nominal spatial resolution of 750 m and temporal resolution of 20s to quantify the likely errors in 5-minute accumulations as a function of temporal sampling and spatial resolution. They found errors of the order of 35% for 2.5-minute sampling for 5-minute accumulations over 4 km^2.

Reducing the interval between volume scans can reduce temporal sampling error. This can be achieved by increasing the rate at which the radar rotates or by reducing the number of elevation angles that are used to scan the volume surrounding the radar. However the radar scanning strategy is limited by other considerations. The revolution rate is often fixed by the maximum range of required observations and by

a requirement to sample a sufficient number of pulses to minimise the sampling error in reflectivity. Often a large number of tilt elevations are required to observe the three dimensional distribution of a storm when the radar is used for meteorological as well as hydrological purposes. These operational limitations place restrictions on the temporal resolution that can be achieved, which may increase temporal sampling error.

The Australian radar network operates on a 10-minute sampling strategy which allows enough time for the comprehensive 3D sample of the volume required for severe weather forecasting as well as enough samples so as to produce reasonable quality hourly rainfall accumulations over medium size catchments. However, a 5-minute sampling cycle is more appropriate for small-scale rainfall measurements required for urban flash-flood warning and severe weather warnings for thunderstorms that have short life cycles. One of the radars with coverage over Sydney operates on a 5-minute cycle.

1.3.1.2 Height sampling

The height of the radar beam above the ground surface, *h*, increases in a non-linear fashion due to the curvature of the earth and refraction of the radar beam through the atmosphere [Doviak and Zrnic, 1984 pp.18-22]. The height of the beam above the elevation of the radar transmitter is given by

$$h = \sqrt{r^2 + (k_e R_e)^2 + 2rk_e R_e \sin\theta} - k_e R_e$$

Equation 1-10

where r is the range to the radar, θ is the elevation angle of the radar beam, R_e is the radius of the earth (≈6372km) and k_e is a constant allowing for refraction of the radar beam path through the atmosphere (≈4/3). Figure 1.1 shows this relationship for radar beams at typical elevation angles. Therefore, the radar estimates the rainfall intensity at some level above ground level, and this is used to infer the rain rate on the ground.

The variability of the vertical profile of rainfall has been identified as a major source of error since the earliest attempts at using weather radar data in a hydrological application [e.g. Wexler, 1948; Harrold *et al.,* 1974] and despite active research has not yet been solved completely [Borga *et al.,* 1997]. Austin [1987] identified six reasons why the rainfall estimated at one elevation might not be the same as the rainfall estimated at a position directly below:

1. Echo enhancement due to the bright band;
2. Growth of raindrops as they fall through fog or low level cloud;
3. Evaporation of raindrops as they fall through dry air;
4. Variation in drop fall speed due to changes in atmospheric pressure;
5. Variation in drop fall speed due to updraughts or downdraughts; and
6. Variation in drop fall velocity due to cross winds.

The height of the radar beam increases with range from the radar until the beam height exceeds the depth of the meteorological system producing the rainfall. In widespread rainfall, the snow aloft melts into rainfall at some height above the ground as it falls through the 0°C isotherm. The melting snowflakes become coated with liquid during the melting process and make large targets for the radar causing a significant increase in radar reflectivity. The large reflectivity returns from the melting snowflakes appear as very bright areas on the cathode ray tube displays that used to be attached to older radar installations. For this reason, the layer through which the snow melts is referred to as the “bright band”.

Bright band contamination causes persistent overestimation of rainfall at the ranges where the radar beam intersects the melting layer, which can be dealt with in a number of ways. In warm weather, the bright band can be avoided altogether by using a low enough beam elevation to scan beneath the bright band. In cooler conditions, radar volume scan information [Andrieu and Creutin, 1995] or observations from a vertically pointing radar [Atlas, 1957; Tilford, 1998] can be used to remove bias caused by the bright band.

Vertical reflectivity profile adjustment techniques have been proposed to adjust rainfall estimates made at different elevations [Joss and Waldvogel, 1990; Joss and Pittini, 1991; Kitchen *et al*., 1994; Andrieu and Creutin, 1995; Joss and Lee, 1995]. These techniques can be regarded as bias corrections since they correct for the mean profile and do not attempt to take into account the random fluctuations. Although bias correction may improve the accuracy of radar-rainfall estimates, the

random error due to sampling at some height above the ground may still cause significant problems in radar estimation of rainfall rates.

1.3.1.3 Spatial sampling

A radar observes reflectivity averaged across a relatively large volume of space. The intensity of the radar beam has an approximately Gaussian pattern [Sherman, 1970], as shown in Figure 1.2, that is symmetrical in all directions about the axis of the beam. The radar also has a beam with a fixed angular width (typically 1°- 2°), so that the beam increases in linear width with increasing distance from the radar. The radar beam integrates out the small-scale features in the rainfall and returns the average instantaneous reflectivity across a volume of space that is of the order of 300 m × 1 km

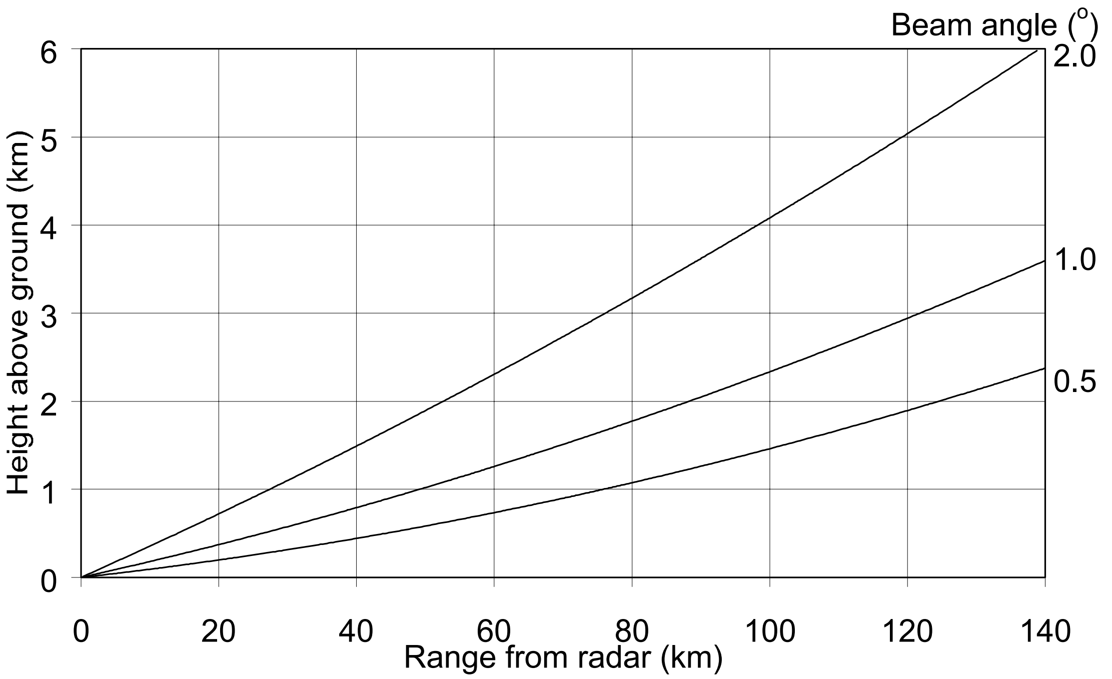

Figure 1.1 Height of radar beam above the ground with range from the radar

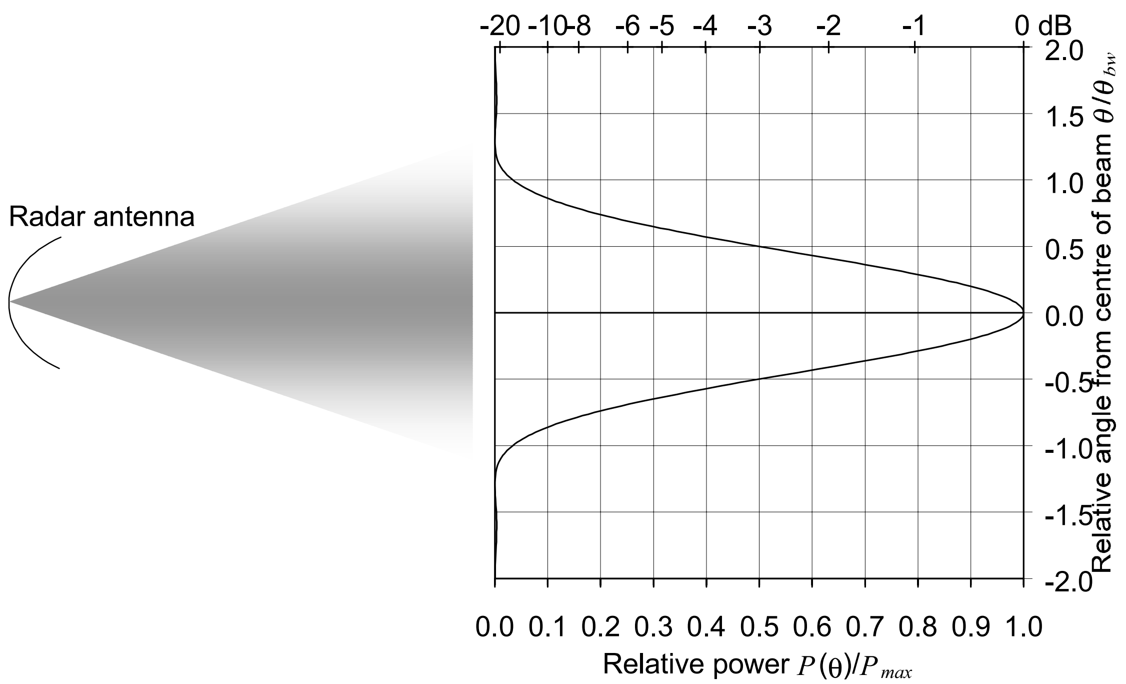

Figure 1.2 Angular distribution of power within a typical radar beam

× 1 km, depending on the beam width and the distance from the radar. The smoothing performed by the radar beam causes error in measurement of reflectivity at scales smaller than the volume sampled by the beam at a particular point. This spatial sampling error increases as the beam width increases or as the distance from the radar to the area of interest increases. Spatial sampling often causes underestimation of small-scale high rainfall intensities at longer ranges from the radar.

1.3.1.4 Ground clutter, anomalous propagation and beam blocking

Interception of the radar beam by fixed objects is the cause of the problems known as ground clutter, anomalous propagation and beam blocking. Figure 1.3 shows the causes of these three effects. The antenna beam pattern shown in Figure 1.2 is a simplification and real antennas produce several other (very much weaker) peaks in power at angles which are much further from the centre of the main beam. These peaks are known as side-lobes. Ground clutter occurs when a side-lobe of the radar beam scanning at a low elevation angle intercepts the surrounding hilly terrain, which then returns a significant echo. Anomalous propagation is also interception of the ground by the radar beam, but this is caused by refraction of the radar beam toward the ground as it passes through layers of the atmosphere with different densities. The radar beam will be partially or fully blocked in the area beyond where it is intercepted by the ground, causing a reduction in the power backscattered from rain in this area. Trees and structures located near the radar can cause similar blockage of the radar beam.

Ground clutter, anomalous propagation and beam blocking can be significantly reduced or possibly even removed by relatively simple strategies, for example by increasing the elevation angle of the radar beam. However increasing the radar beam elevation angle may cause increases in errors due to beam height. Ground clutter does not move and therefore can be removed relatively easily by using a predetermined map of the ground clutter [Gabella and Perona, 1998]. Doppler radar information can be used, when available, to identify and remove stationary echoes that are usually the result of ground clutter or anomalous propagation. The extent of beam blocking can be determined from the topography of the surrounding areas, and deterministic corrections can be applied in the partially blocked areas [Andrieu *et al*., 1997; Gabella and Perona, 1998].

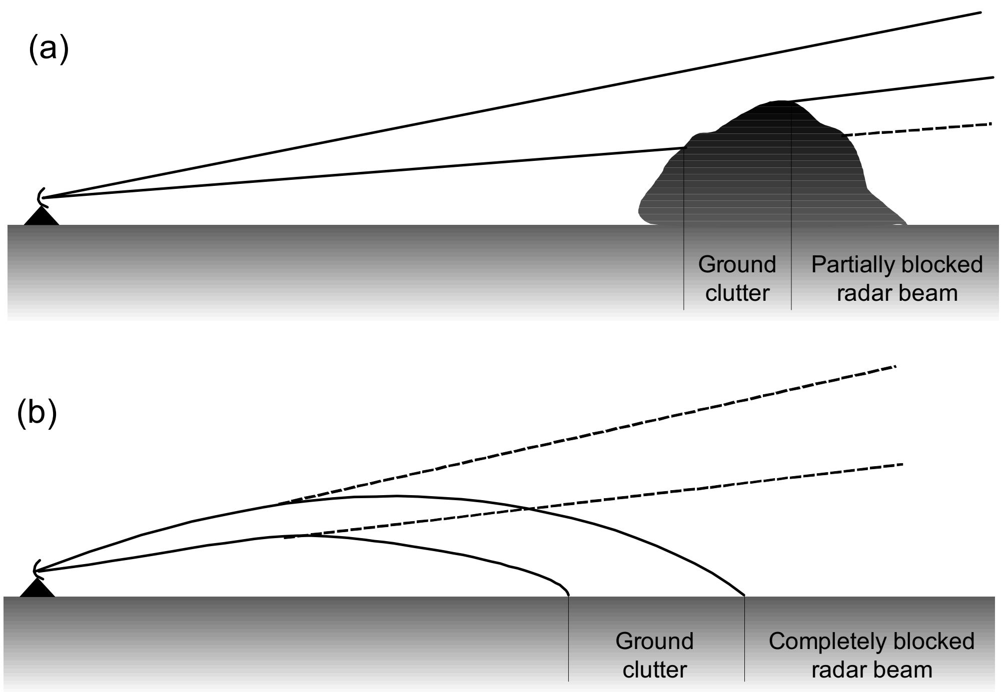

Figure 1.3 Diagram of beam interception errors: (a) ground clutter and partial beam blockage caused by interception of terrain; and (b) ground clutter and complete beam blockage caused by anomalous propagation of the radar beam

1.3.1.5 Beam attenuation

The power of the radar beam is attenuated by vibration of particles in the atmosphere and absorption by water. The sensitivity of a radar signal to attenuation depends on the wavelength of the radiation transmitted by the radar and the intensity and nature of the precipitation. In general, attenuation is a severe problem for radars transmitting at X-Band (wavelength of radiation of 2.8 cm), can be a problem for radars transmitting at C-Band (wavelength of radiation of 5.5 cm), and is not a problem for radars transmitting at S-Band (wavelength of radiation of 10.7 cm). Significant attenuation can also take place if a radome (the structure that covers the antenna) loses its hydrophobic properties and becomes coated with a layer of water during rainfall. Hildebrand [1978] developed an iterative scheme for computing the attenuation of the radar beam through rainfall. This algorithm can (in principle) be used to correct the rainfall intensity fields for attenuation of the radar beam, but it assumes that the Z-R relationship is known *a priori*, which is not the case and is numerically unstable. Attenuation is particularly significant in C-Band observations of heavy rainfall or wet hail, which are both common phenomena on the Australian east coast.

1.3.1.6 Radar electrical calibration error

The measured reflectivity is calculated from Equation 1-3, which uses the fraction of the transmitted power that is backscattered to the radar. An accurate measurement of reflectivity depends upon the accuracy in estimates of the transmitted power and power losses in the transmitter and antenna. However, the power transmitted by the radar can change with time, causing inaccuracies in the estimated value of transmitted power. If the emitted power is not calibrated regularly then there could be inaccuracy in measurements of reflectivity. This error can be minimised by regularly calibrating the power output of the radar. The magnitude of any persistent bias in emitted radar power can also be determined by comparing long-term accumulations of radar derived rainfall over large areas with accumulations determined from the raingauge network over the same period.

1.3.1.7 Quantisation of reflectivity

The transmission of radar data from the radar to the point of application has been a major source of sampling error in the past and continues to influence the decisions regarding the spatial, temporal, and radiometric resolution of the rain field as used by the applications. Apart from the obvious data compression technique of zero suppression used on many radar systems, the reflectivity data have often been represented by using a limited number of intensity levels to enable further data compression prior to transmission. For example, it is for this reason that 16-level radar data forms the bulk of the Australian radar archive. Quantisation is a deterministic process, which can introduce error into an individual reflectivity measurement of up to half the class width. Quantisation introduces random error and does not bias rainfall measurements if the distribution of rainfall intensity is log-normal.

Historical radar data are necessary for the off-line calibration and validation of flood forecasting models and therefore the consequences of using historical radar data with low radiometric precision need to be determined. Furthermore, while it is true that the technology to transmit data at very high transmission rates is now available, it is not always possible to use this technology at remote radar sites. Cluckie *et al*. [1991] and Pessoa *et al*. [1993] found that 8-level radar data could provide unbiased rainfall information that can be used in rainfall-runoff modelling. Cluckie *et al.* [1991] found that the rainfall-runoff model acted as a low pass filter that damped the errors introduced by reducing the radiometric resolution.

1.3.2 Reflectivity to rainfall conversion errors

Radars do not measure rainfall intensity directly. The reflectivity must be converted to rainfall intensity using some form of transfer function. This transfer function is commonly referred to as the *Z-R* relationship and, based on the theoretical argument in Section 1.2, is assumed to be a power law written in the form $Z = aR^b$. The parameters of the Z-R relationship depend upon the distribution of raindrop sizes that have been sampled and the terminal velocity of the raindrops as a function of diameter. The raindrop size distribution varies in space and time depending on the microphysical processes that are active in producing the rainfall, causing variability in the *Z-R* relationship in both space and time. The presence of strong up or down drafts can either hold large raindrops aloft for an extended period leading to low rain rates relative to the measured reflectivity, or accelerate the drops

downwards leading to high rain rates relative to the measured reflectivity. Therefore, there is not a one-to-one reflectivity to rainfall relationship and different rain rates could be associated with the same reflectivity.

Quality control of all the data (including the gauge data) is the single most important step of any precipitation analysis [Steiner *et al.,* 1999]. The presence of measurement noise makes it difficult to detect changes in the drop size distribution across a rainfall field in space and time. The most basic calibration method is to determine a fixed climatological *Z-R* relationship using a long sequence of radar data together with either raingauge or disdrometer (a device that measures the size distribution of raindrops) measurements. This climatological relationship represents the "average" relationship for the particular climate and radar.

Significant random deviations arise from this one-size-fits-all approach to radar calibration due to the variability in the drop size distribution both within and between storm events. One method of correcting for the variations in the *Z-R* is use a disdrometer to track the changes in the drop size distribution. The difficulty with this approach is that the disdrometer samples a small area and therefore there are significant sampling errors in short-duration estimates of the drop size distribution. Disdrometers are also too expensive to deploy in large numbers under the radar umbrella.

The alternative approach is to use a network of raingauges and then use a statistical technique to adjust the *Z-R* relationship on the basis of the co-located gauge and radar data. Radar measurements are typically areal averages over 1 to 4 km^2 whereas a raingauge measures accumulations over an area of about 3×10^{-8} km^2. Furthermore, the gauge is usually a tipping bucket type gauge with a resolution of between 0.2 mm and 1 mm, which makes it difficult to measure light rain with sub-hourly temporal resolution. The height of the radar measurement is typically 1-2 km above ground level, and it could take 5-10 minutes for raindrops to fall to the ground after the radar measurement. Therefore, there can be significant wind drift in the time that the rainfall takes to fall from the level of the radar measurement to the ground. Gauge to radar comparisons are therefore fraught with measurement and sampling errors, which can only be ameliorated through spatial and or temporal averaging. Typically, hourly accumulations of radar and gauge data are used in these calibration methods.

If the data are being used as input into hydrological models, the most significant error is a bias in the mean areal rainfall over the catchment, as any small-scale errors will tend to be smoothed in the hydrological modelling process [Jordan, 2000]. The radar data can be adjusted to provide an unbiased storm total using a single adjustment factor for the duration of the event for off-line applications, or through the sequential estimation of the adjustment factor using a statistical bias estimation algorithms such as Smith and Krajewski [1991] and those evaluated by Anagnostou, *et al*. [1998].

2. Climatological Calibration

2.1 Introduction

The climatological *Z-R* relationship for a radar is a function of both the nature of the rainfall being measured and the radar itself. In particular, the multiplicative constant *a* in the *Z-R* relationship will include any power losses in the radar system that have not been accounted for in the electrical calibration of the radar. The climatological *Z-R* relationship is used as the default in the absence of any evidence that there is a statistically significant deviation from this relationship at a particular time. The basic method is to collect a very large sample of gauge and radar accumulations and select a *Z-R* relationship that minimises an error measure. The selection of the error statistic depends on the applications that use the radar data. If the data are used for hydrological modelling then it is very important to minimise any bias in the rainfall since hydrological models typically amplify systematic errors. On the other hand, if the data are used in a flood warning system that has a very low tolerance for false alarms, a relatively high exponent in the *Z-R* relation should be selected so as to protect against very large over-estimations of rainfall intensity in situations when the radar signal is contaminated by hail or bright band.

2.2 Radar data

Archived data from Darwin, Sydney, and Melbourne were used in this study as these three radars have the most complete record out of the radars that serve the capital cities and each represents a different climatological region. The location of each of the radars and the period of the record used in this study are found in Table 2.1.

The raw radar data are in three-dimensional polar format, and are archived in 16 intensity levels. The first step was to convert these polar data into Cartesian grids with 256 km x 256 km extent and 2 km, 10 minute resolution. The data sets for the three radars are intermittent with gaps due to problems with the radar, communications and with reading the archive tapes. The fraction of good data for Darwin, Sydney, and Melbourne is given in Figure 2.1, Figure 2.2, and Figure 2.3 respectively. The daily accumulation based on radar data will be underestimated if there are missing periods during the day, therefore only those days with more than 100 out of the maximum 140 scans were included in the analysis. An analysis of raingauge data showed that there were nine days of heavy rainfall (> 20 mm) missing from Sydney, and eight days of significant rainfall missing from the Darwin data set. Substantial progress has been made by the Bureau of Meteorology to develop a more systematic radar data archive since these data were collected, and the availability of more recent radar data is much better than this.

The radar reflectivity was converted to rainfall using the standard *Z-R* relationship for mid-latitude widespread rainfall for Sydney and Melbourne ($Z=200R^{1.6}$), and the Steiner *et al.* (1995) relationship derived for Darwin ($Z=170R^{1.2}$), and accumulated into daily rainfall totals.

Table 2.1 Summary of radar data used for the climatological calibration study

	Latitude	Longitude	Start year	End year	Sample size (days)
Darwin (Berrimah)	12.46°	130.93°	1995	1997	480
Melbourne (Laverton)	37.85°	144.75°	1995	1997	630
Sydney (Letterbox)	34.26°	150.87°	1996	1997	420

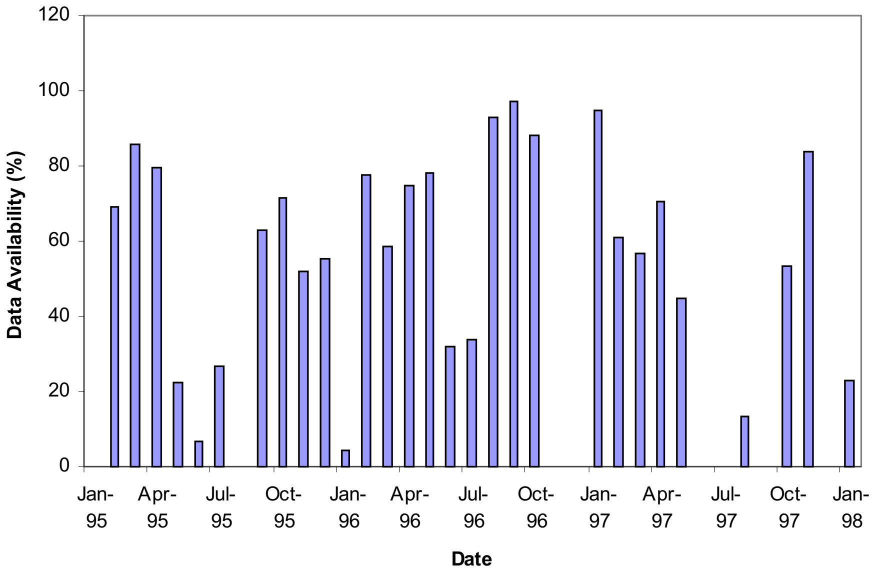

Figure 2.1 Percentage of data present in the Darwin radar record

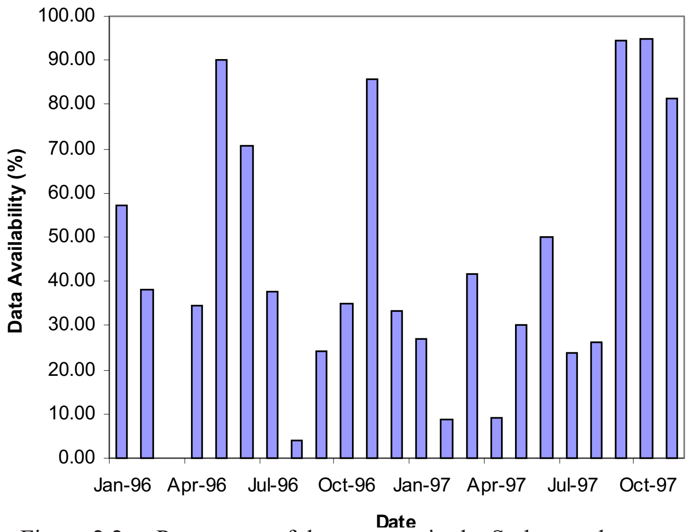

Figure 2.2 Percentage of data present in the Sydney radar record

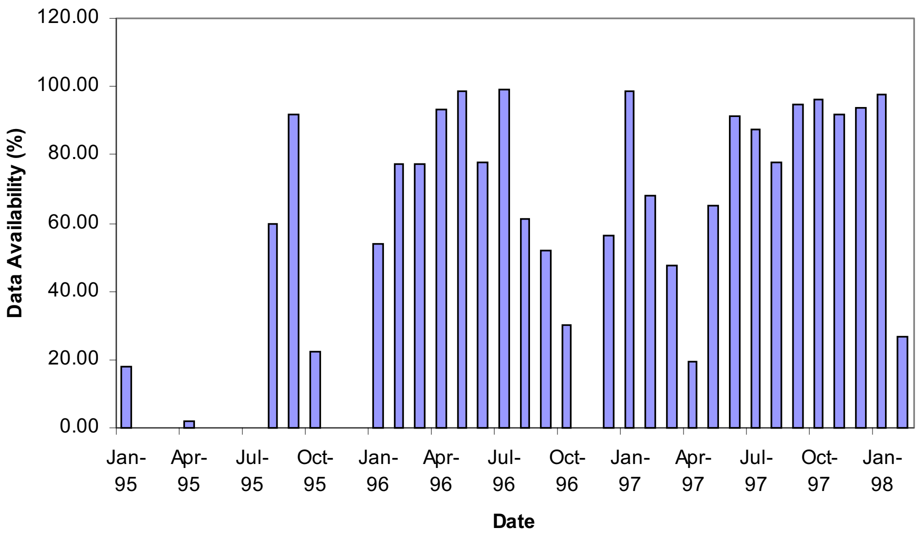

Figure 2.3 Percentage of data present in the Melbourne radar record

2.3 Raingauge data

There are about 7000 daily rainfall stations in Australia, many of them near the capital cities. A search of the raingauge database revealed 70 gauges within 128 km of the Berrimah radar. The networks around Sydney and Melbourne were larger with about 250 gauges each. These gauge networks are much more dense than the equivalent short-duration gauge networks and provide good estimates of mean areal daily rainfall. The mean areal rainfall was calculated as the arithmetic mean of the gauges within 128 km of the radar. Figures 2.4 to 2.6 show the raingauge networks for the Melbourne, Darwin, and Sydney areas respectively.

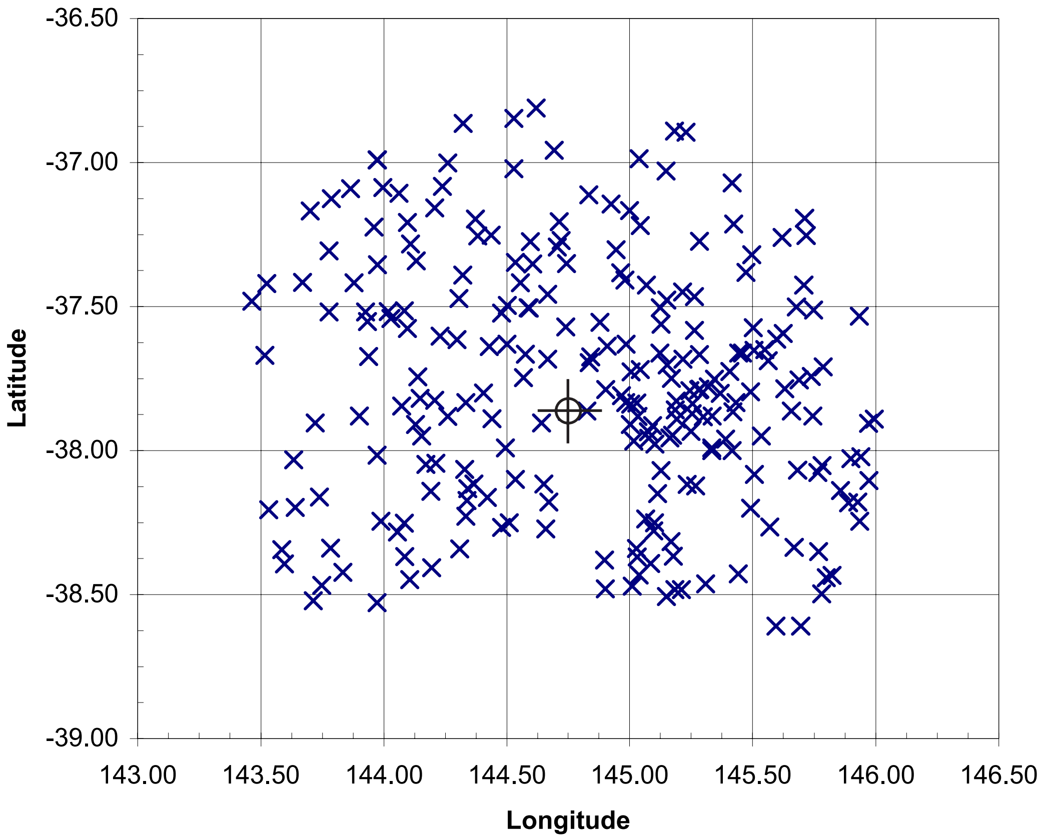

Figure 2.4 Network of daily raingauges for Melbourne. The Melbourne radar position is shown as ⌖

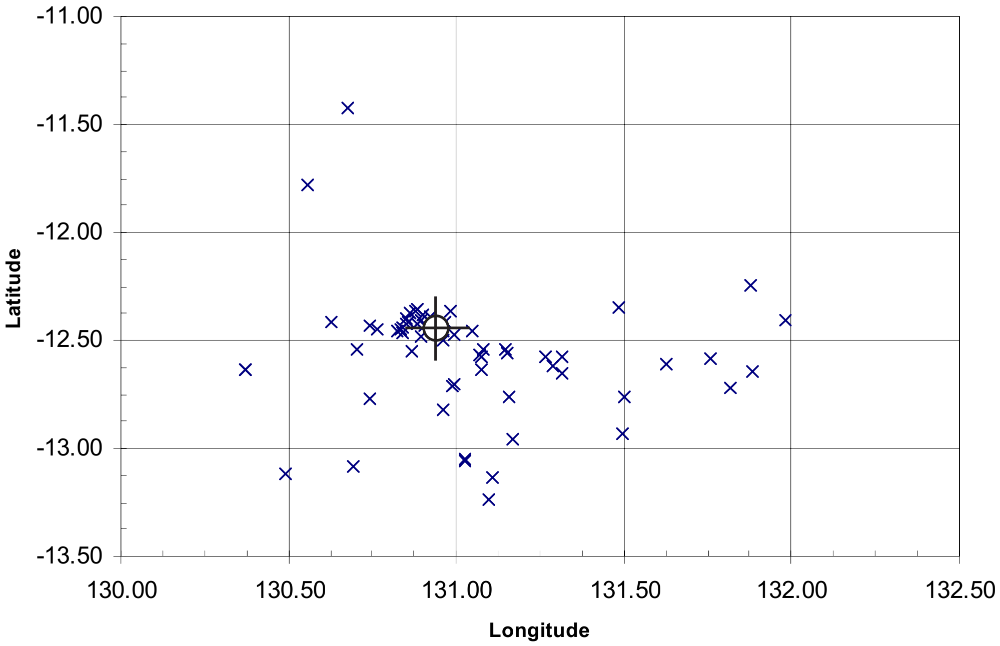

Figure 2.5 Network of daily raingauges for Darwin. The Darwin radar position is shown as ⊕

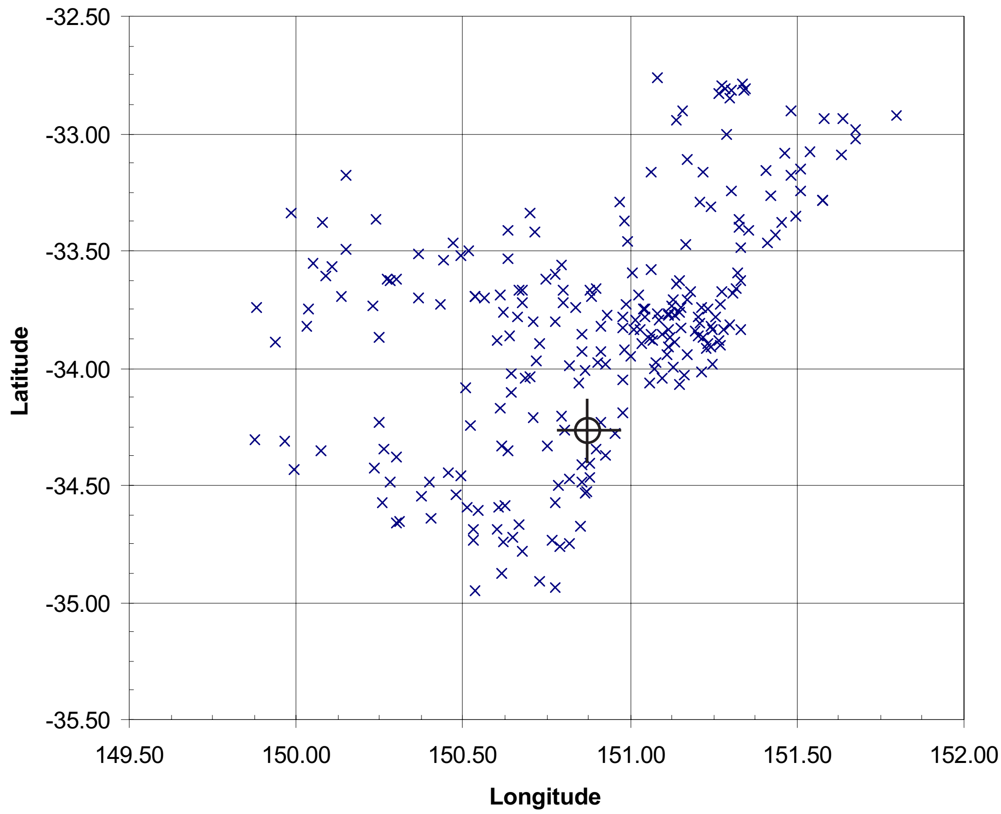

Figure 2.6 Network of daily raingauges for Sydney. The Sydney radar position is shown as ⊕

2.4 Method

The mean gauge rainfall based on the gauge data was defined as

$$\overline{G}_j = \frac{1}{N}\sum_{i=1}^{N} g_{ij} \qquad \text{Equation 2-1}$$

where g_{ij}, i=1…N are the N gauge measurements on day j.

The mean radar rainfall was defined as

$$\overline{R}_j = \frac{1}{N}\sum_{i=1}^{N} r_{ij} \qquad \text{Equation 2-2}$$

where r_{ij}, i=1…N are the values of the radar accumulation field for day j for the 1x1 km radar pixels that contain the N rainfall gauges, computed using an initial *Z-R* relationship .

Measures of the gauge-radar error include

Mean Error,

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(\overline{R}_i - \overline{G}_i\right) \qquad \text{Equation 2-3}$$

Mean Absolute Error,

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\overline{R}_i - \overline{G}_i\right| \qquad \text{Equation 2-4}$$

Root Mean Square Error,

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\overline{R}_i - \overline{G}_i\right)^2} \qquad \text{Equation 2-5}$$

Bias,

$$B = \frac{\sum_{i=1}^{n}\overline{G}_i}{\sum_{i=1}^{n}\overline{R}_i} \qquad \text{Equation 2-6}$$

where n is the number of mean areal daily rainfall totals in the record.

The objective is to select the multiplicative term in the *Z-R* relationship so as to minimise the error measure while keeping the exponent b fixed. If the objective function is to correct for the bias B given an initial value for a then the relationship becomes

$$Z = aB^{-b}R^{b} \qquad \text{Equation 2-7}$$

2.5 Results

The comparison of point gauge and radar daily accumulations gives an idea of the accuracy of the radar at the resolution of single pixels. Figure 2.7 shows the time series of daily rainfall recorded by gauge G68007, Sydney, and the daily radar accumulation for the radar pixel at the same location. The low correlation between the time series of point radar and gauge data is clearly evident. A time series plot of mean areal gauge and radar rainfall for a month of the Darwin data is shown in Figure 2.8. There appears to be some persistence in the radar under and over-estimating the mean areal daily rainfall. Significant errors are possible, e.g. the 20 mm over-estimation on 14 December.

Scatter plots of mean gauge and radar mean areal daily rainfall for Darwin, Melbourne, and Sydney are shown in Figures 2.9, 2.10, and 2.11 respectively. The scatter of the points about the regression line show that the *RMSE* does appear to increase with increasing gauge rainfall, but there is still a significant *RMSE* for low daily rainfall totals and therefore the relative accuracy of the radar estimation increases with increasing rainfall.

The results in Table 2.2 show that a climatological *Z-R* relationship has a RMSE of about 3-4 mm for daily rainfall accumulations in Sydney and Melbourne and 7-8 mm for Darwin where the mean rainfall is higher. This implies that approximately 30% of the rain days will have errors that exceed these values. Some of the observed error is due to missing data in the radar data set so these errors are likely to be conservative.

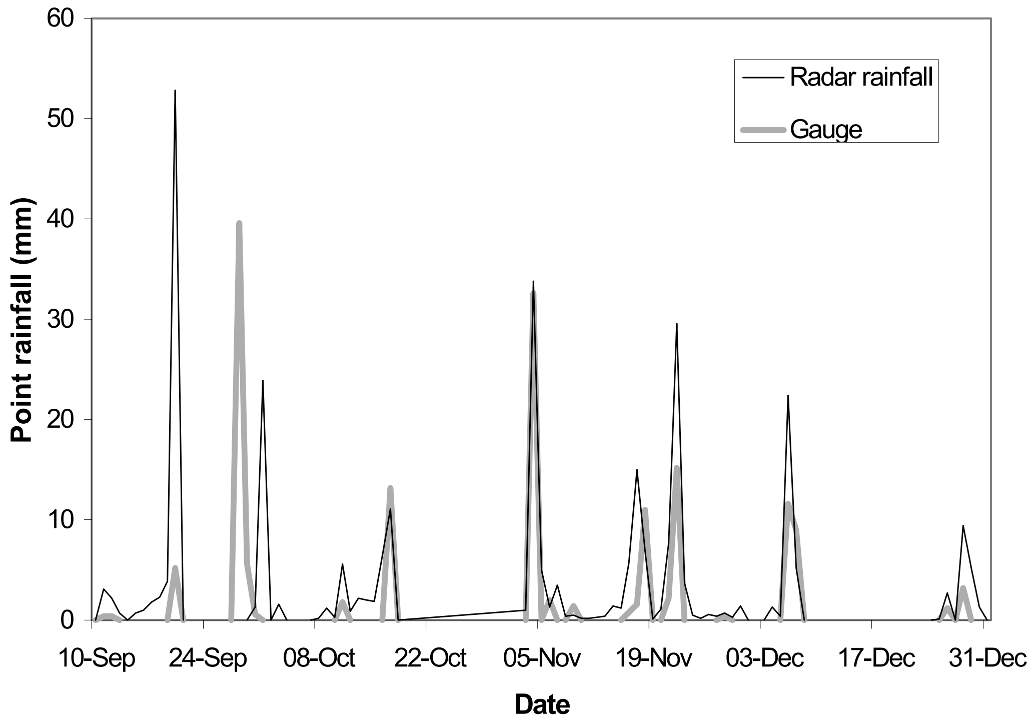

Figure 2.7 Time series of daily rainfall at gauge G68007, Sydney, and the daily rainfall at the same locations measured by the radar

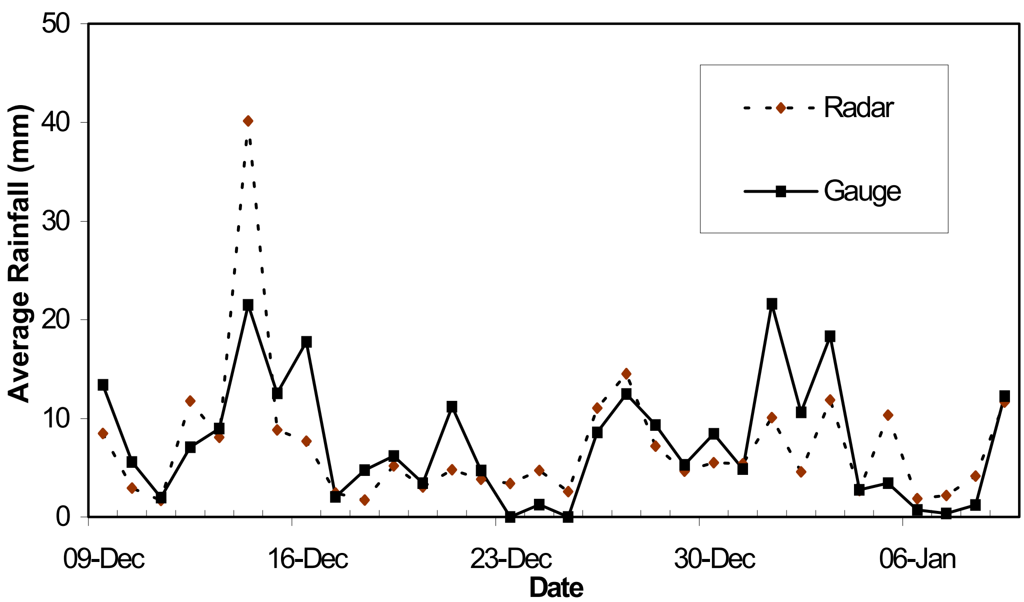

Figure 2.8 Time series for mean areal daily gauge and radar rainfall over Darwin using $Z = 115R^{1.2}$

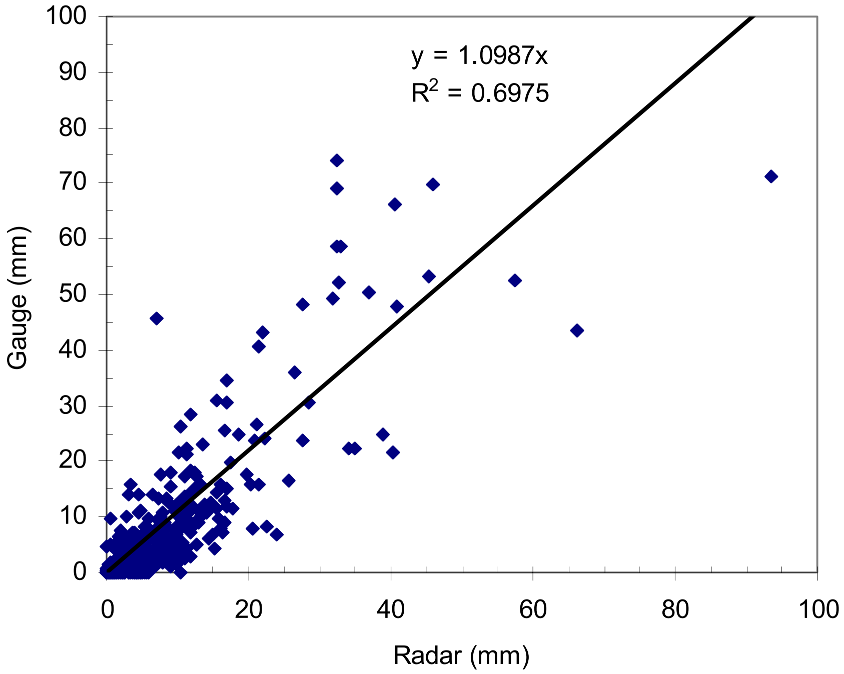

Figure 2.9 Scatter plot of mean areal daily radar and gauge accumulations for Darwin based on $Z = 115R^{1.2}$

Table 2.2 Summary of results for climatological *Z-R* calibration

	Sydney	**Melbourne**	**Darwin**
Number of days	420	630	480
Number of gauges	252	250	74
ME (mm)	-0.017	-0.031	-0.077
MAE (mm)	1.87	1.35	3.57
RMSE (mm)	3.7	2.97	7.36
R^2	0.59	0.50	0.70
B	1.2	0.78	1.3
Initial *a*	200	200	170
Adjusted *a*	280	75	115
b	1.6	1.6	1.2

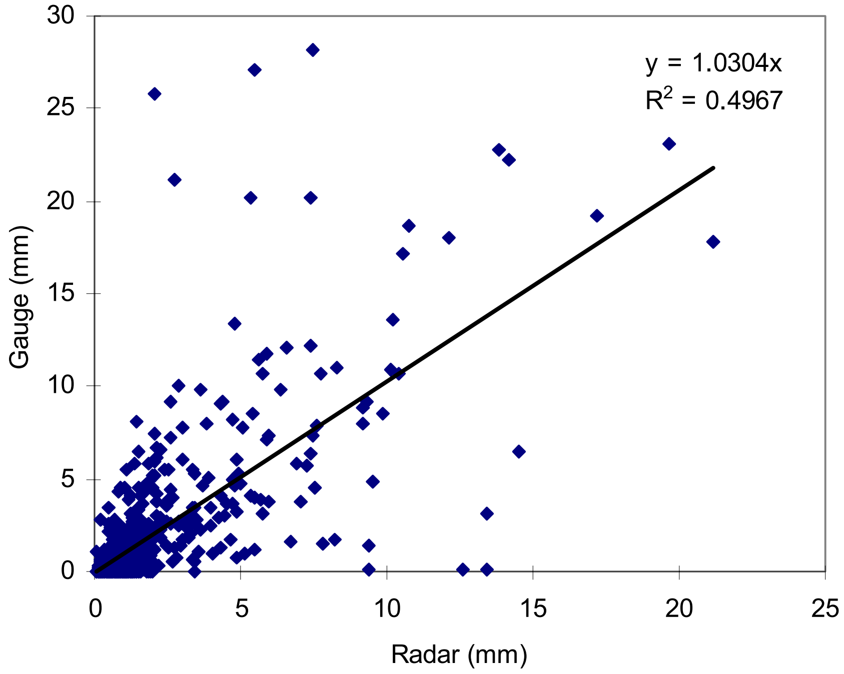

Figure 2.10 Scatter plot of mean areal daily radar and gauge accumulations for Melbourne based on $Z = 75R^{1.6}$

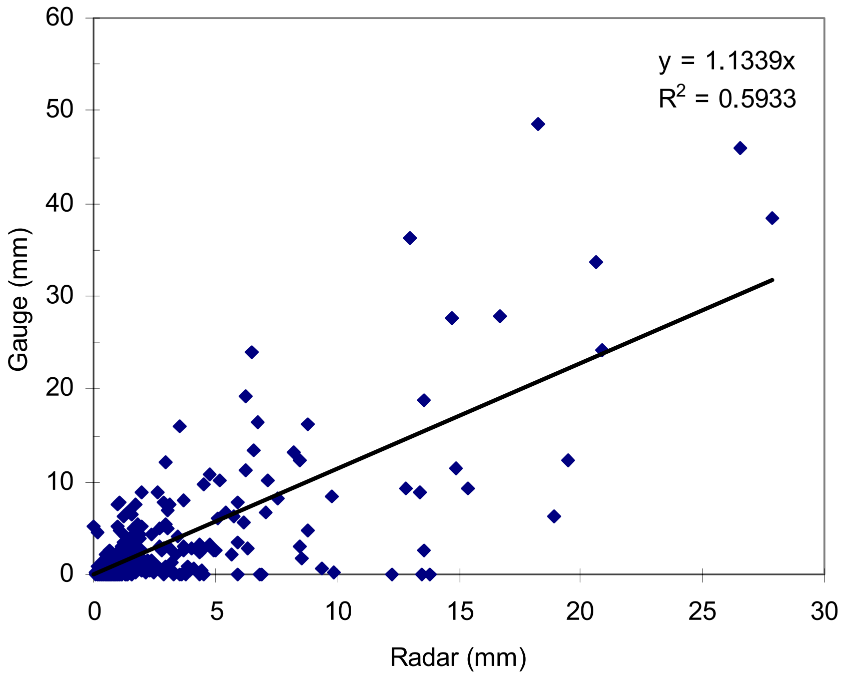

Figure 2.11 Scatter plot of mean areal daily radar and gauge accumulations for Sydney based on $Z = 280R^{1.6}$

3. Event calibration for Sydney

This chapter describes the calibration of weather radar data for the Sydney area using hourly data from a rainfall gauge network on an event basis or at hourly steps within the event. Calibration at hourly steps allows the results to be used in hydrological models that require continuous parameter updating such as in real-time flood forecasting and will be investigated in the following chapter.

Calibration of the *Z-R* relationship requires storms of diverse characteristics that originate from different meteorological systems such as thunderstorms and frontal storms. An average *Z-R* relationship for each event (off-line event based calibration) can be established using an appropriate calibration strategy. The variation of the calibrated parameters with storm characteristics can then be examined. If significant differences in *Z-R* relationships for rainfall from different meteorological conditions are found, then the use of an appropriate *Z-R* that depends on the synoptic type should lead to improvements in real-time estimates of rainfall compared with using a single climatological *Z-R* relationship.

3.1 Data for Calibration of Z-R Relationship

Seven storms of different characteristics that occurred in the Sydney area were selected for this study. These included short duration convective cells (thunderstorms), as well as widespread frontal storms. This allows for the investigation of variation of parameter values of the *Z-R* relationship with different types of storms. Details of the selected storms are given in Table 3.1.

3.1.1 Radar data

Observations at the Letterbox radar, located about 45 km southwest of Sydney, were used in this study. The radar scans the territory around it every 10 minutes and produces snapshots of reflectivity in dBZ. The radar data were converted into rainfall maps covering a 128 km x 128 km square, centred on the radar with a 2 km and 10 minute resolution, using the climatological *Z-R* relationship for Sydney $Z = 280R^{1.6}$ found in Chapter 2. These 10-minute rainfall intensity maps were then accumulated into 1-hour rainfall maps. Examples of such maps are given in Figures 3.1 and 3.2.

Table 3.1 Details of the rainfall events used for event calibration in Sydney

Date	Type	Description
19 /1/1996	Convective	Double peaked scattered storm with moderate intensity of about 12 hours duration
04/5/1996	Widespread	Widespread storm with moderate intensity
30/8/1996	Widespread	Widespread frontal storm with high intensity and long duration
06/12/1996	Widespread	Widespread rainfall with low intensity
19/121997	Convective	Scattered storm with low mean areal intensity and short duration
03/1/1998	Convective	Scattered storm with low intensity and short duration
11/11/1998	Widespread	Storm with low mean areal intensity and longer duration

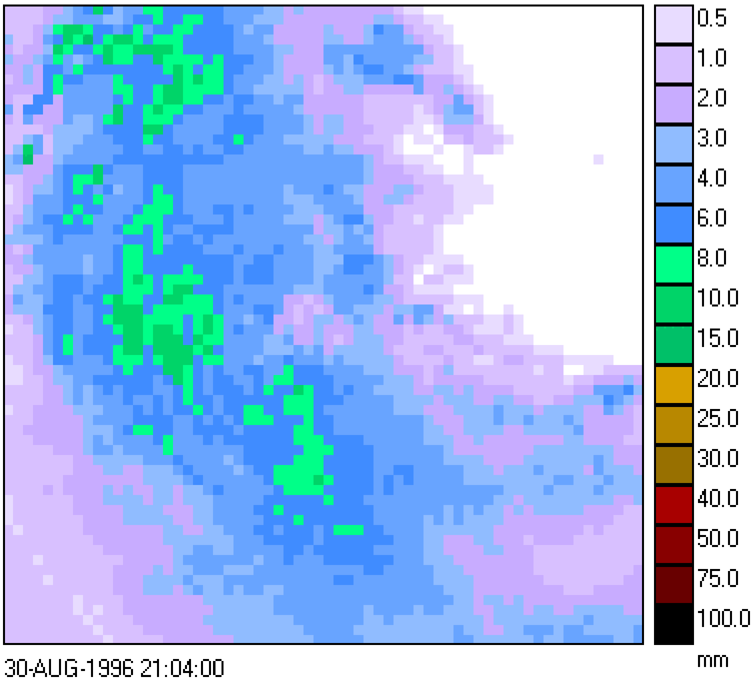

Figure 3.1 Maximum 1-hour radar rainfall accumulation during the 30/8/1996 event using the climatological *Z-R* relationship. This is an example of a typical “widespread” rainfield. The image is a 128 x 128 km square centred on the Letterbox radar, 2 km resolution.

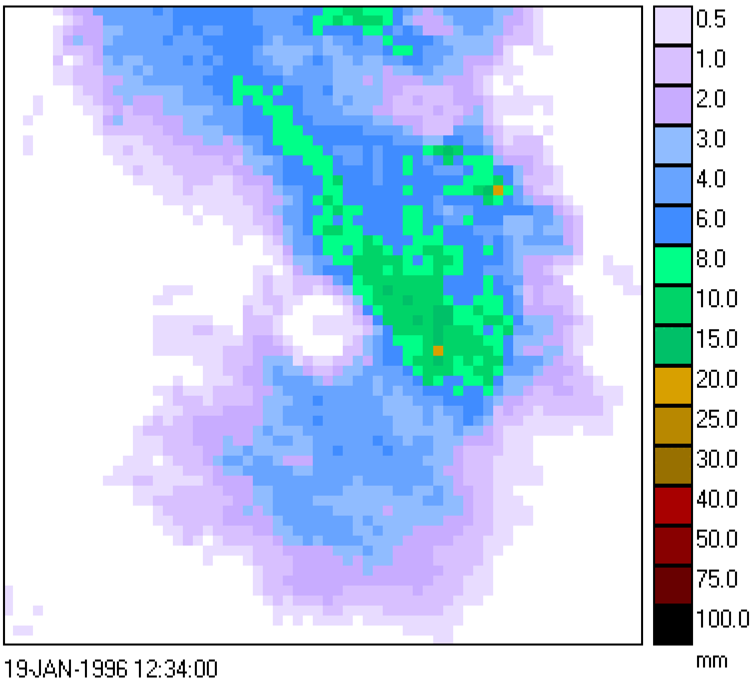

Figure 3.2 Maximum 1-hour radar rainfall accumulation during the 19/1/1996 event using the climatological *Z-R* relationship. This is an example of a typical “convective” rainfield. The image is a 128 x 128 km square centred on the Letterbox radar, 2 km resolution.

3.1.2 Raingauge Data

Hourly gauged rainfall data required for this study were obtained from continuously recording tipping bucket rainfall stations that are either telemetered or on data loggers. Data from ALERT stations were used as the primary source in this study; these stations report every tip of their raingauge bucket via radio telemetry to the Bureau of Meteorology to facilitate real-time forecasting. ALERT stations send a signal to the base station every time the bucket (usually 1 mm capacity for stations in Sydney area) tips. The basic ALERT data are therefore in the form of a cumulative rainfall series in increments of the bucket capacity with time assigned to each tip. The data files are subsequently subject to quality checks.

The rainfall data from ALERT stations were supplemented by pluviograph data from a number of stations operated by Bureau of Meteorology. These data are stored at 6-minute intervals and rainfall totals in hourly intervals were extracted for each storm period for those raingauges that have recorded at least 1 mm rainfall during the storm event. Thus, the number of raingauges used in calibration varies with the type and extent of the storm. Based on this criterion, the number of stations with non-zero rainfall ranged from about 60 stations for widespread long-duration events to about 20 stations for calibration of scattered short-duration events. The hourly accumulation of gauged rainfall was synchronised with the timing of the radar measurements, noting that the radar measurements are not usually made at regular clock-hour times.

Radar and gauged rainfall data used in this study were subject to screening for consistency and obvious errors before use in calibration. Examination of radar images revealed that the radar rainfall field in the near vicinity of the radar station (within about 10 km radius) was consistently lower than the rainfalls recorded at gauging stations for all storm events, and so a minimum range for radar measurements of 10 km was used and data from the two rainfall stations nearest to the radar (7201 and 7695) were not used in calibration procedures.

It is also possible for the gauged data to be erroneous, particularly in the case of ALERT data, due to the relatively large volume of the tipping bucket and problems in transmission of signals etc. Gauged rainfall accumulations were checked against rainfalls from other nearby stations in situations where clear inconsistencies were shown between radar rainfalls and gauged rainfall values. A few likely erroneous gauged data were omitted from calibration procedures on this basis.

3.2 Method

The strategy of calibration was to assign a suitable value for parameter *b* from previous studies and then calibrate the parameter *a*. A value of $b = 1.6$ as recommended in Chapter 2 for the Sydney area, was adopted in this study. In addition, $b = 1.5$ and 1.4 were also tested. Preliminary values for parameter *a* that produced unbiased total rainfall over the ensemble of events were calculated to be 280, 340 and 400 for $b =$ 1.6, 1.5 and 1.4 respectively.

For each storm event, three data files of fields of rainfall accumulated over hourly intervals were derived from respective dBZ reflectivity fields using the above *Z-R* relationships. The starting time for accumulation was set to be coincident with a radar volume scan time (eg. 7:04) in order to eliminate the necessity for interpolation between adjacent images.

Each radar rainfall field was sampled at the location of each raingauge and the total hourly rainfall for time *i* was calculated using

$$\overline{G_i} = \sum_{j=1}^{N} g_{ij} \qquad \text{Equation 3.1}$$

$$\overline{R_i} = \sum_{j=1}^{N} r_{ij} \qquad \text{Equation 3.2}$$

where

g_{ij} , are the hourly gauged accumulations for time i, i = 1,…*n* hours, gauge j, j = 1,..*N* gauges in the network.

r_{ij} , are rainfalls at the radar pixel nearest the gauge for *i*=1,..n hours, *j*=1,..*N* gauge locations in the network.

Two calibration methods were tested, viz. equalising the storm totals and minimising RMSE.

3.3 Results

The performance of the two calibration strategies described in Section 3.2 was tested assuming b = 1.6 and then calibrating the parameter a for the seven storm events. The results are given in Table 3.2. Hourly average radar rainfalls computed using the two calibration strategies are compared for the storm event on 30th August 1996 in Figure 3.3.

Table 3.2 Comparison of results from two calibration strategies for b=1.6

Date	**Calibration value of *a***		***RMSE* (mm)**	
	Minimising *RMSE*	**Equalising storm totals**	**Minimising *RMSE***	**Equalising storm totals**
19/01/1996	440	430	1.24	1.30
04/05/1996	67	61	1.96	1.98
30/08/1996	50	45	2.43	2.64
06/12/1996	620	590	0.07	0.10
19/12/1997	390	373	0.07	0.07
03/01/1998	300	304	0.12	0.13
11/11/ 1998	268	230	0.24	0.27

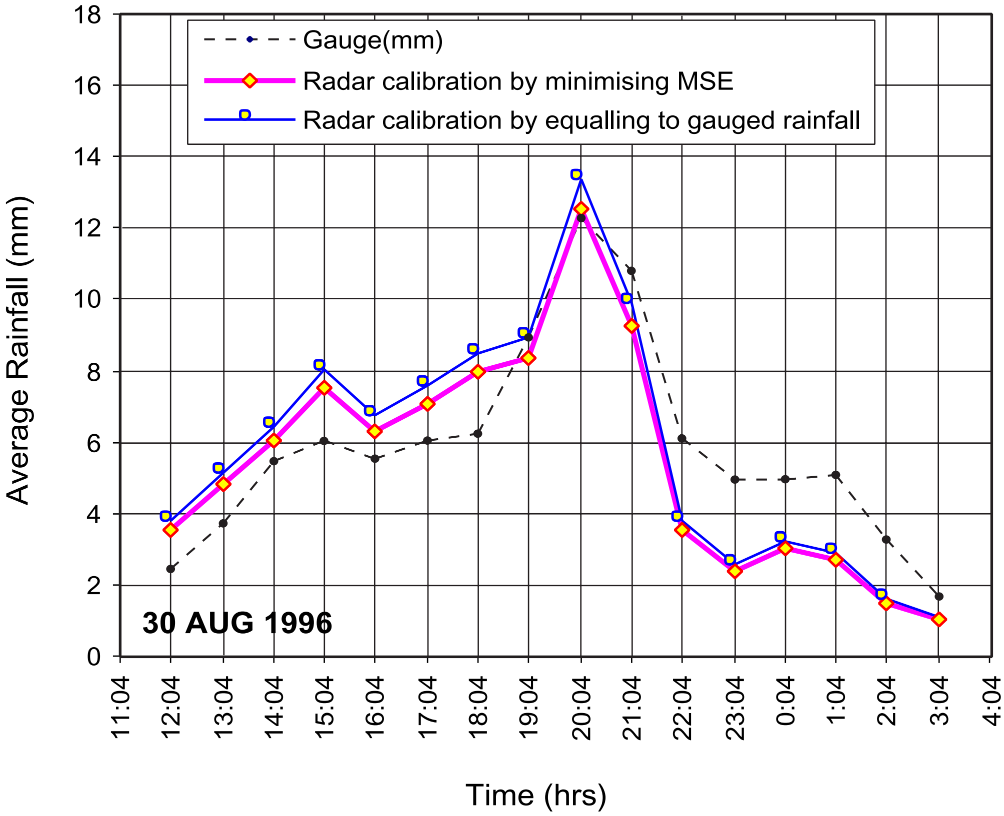

Figure 3.3 Comparison of hourly average rainfall time series from two calibration strategies for the 30/08/1996 event

It could be observed that the two methods gave very similar results. The value of *a* derived by minimising *RMSE* tended to be slightly higher than that derived by equalising the storm totals.

3.3.1 Optimal choice of *b*

Sensitivity of the *RMSE* to the value of *b* was tested for two widespread long duration storms (30/8/1996, 11/11/1998) and one convective storm (03/01/1998). Parameter *a* was calculated for values of *b* = 1.6, 1.5 and 1.4, the results are given in Table 3.3 and Figure 3.4. It is evident that the *RMSE* is quite insensitive to the value of *b* over a wide range so the pragmatic strategy of fixing the exponent *b* and adjusting *a* accordingly has considerable merit.

3.3.2 The variation of *a* with rainfall event

The parameter *a* of the fundamental Z-R relationship with *b* = 1.6, was estimated for the seven storm events described in Section 3.1. Calibrated parameter values are given in Table 3.4. Hourly series of arithmetically averaged data were used to calculate the RMSE and coefficient of determination (R^2) between the radar and gauge data. These two performance indices are also given in Table 3.4.

The calibrated values for *a* were found to vary widely across the seven events, ranging from 50 to 620, with 4 values ranging between 250 and 450. Generalisation of values of *a* for different storm types is discussed in the following section.

The *RMSE* of around 1-2 mm for the radar hourly mean areal rainfall estimates should be compared against the mean hourly rainfall intensity for the storms from which they were derived. It is evident that the hourly radar rainfall estimates will have a large relative error for the smaller events (over 100% for the 19/01/1996 case), but generally the relative errors were about or less than 25%.

The R^2 between the hourly average radar rainfalls and corresponding gauge rainfalls ranges from 0.61 to 0.96, except for the event on 04/05/1996. An examination of Figure 3.6 suggests this may be more the result of data error from a possible shift in time of one hour between the two rainfall records. The time series plots shown in Figure 3.5 to Figure 3.11 indicate reasonable agreement between the two series, although a tendency to overestimate radar rainfall during the initial part of the storm can be seen, particularly for multi-peaked events. One possible explanation is that once the radome gets wet, the water adhering to the surface may cause signal attenuation, so that the reflectivity measured during the remaining duration of the storm would be reduced.

Table 3.3 Sensitivity of *RMSE* to choice of *b*

Date	***RMSE***			***a***			***R^2***		
	b=1.6	*b*=1.5	*b*=1.4	*b*=1.6	*b*=1.5	*b*=1.4	*b*=1.6	*b*=1.5	*b*=1.4
30/08/1996	1.56	1.55	1.56	50	64	81	0.76	0.78	0.79
11/11/1998	0.49	0.49	0.49	268	295	325	0.61	0.60	0.60
03/01/1998	0.35	0.35	0.35	300	340	393	0.92	0.91	0.89

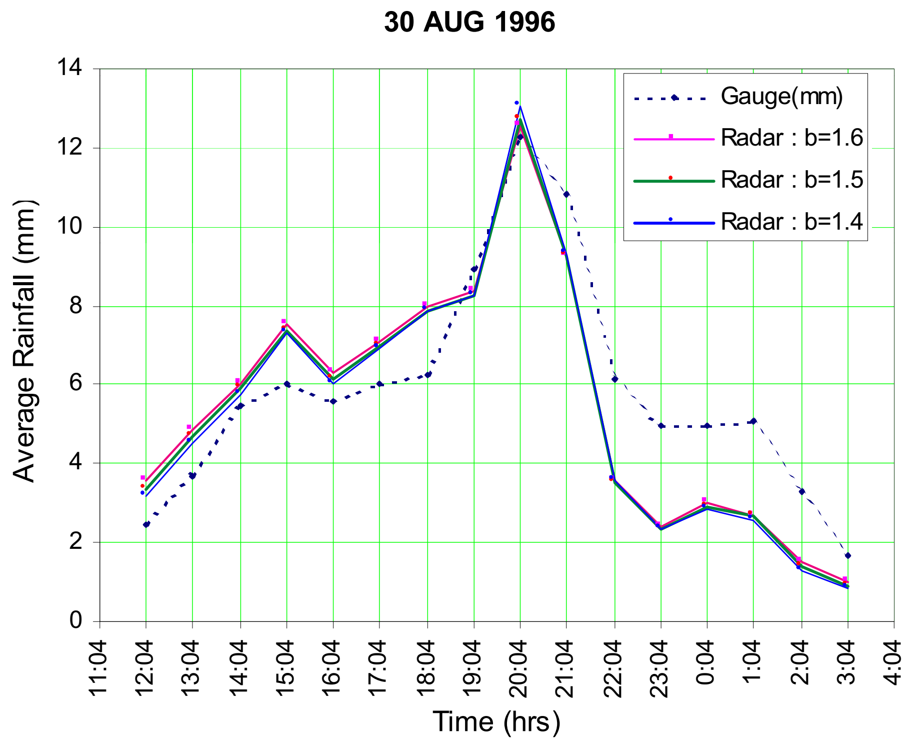

Figure 3.4 Radar rainfall estimation for 30/08/1996 using *b* = 1.4, 1.5, and 1.6

Table 3.4 Estimated value for a, given that b = 1.6, for the 7 Sydney events

Storm event	Storm total (mm)	Storm duration (hours)	*a*	*RMSE* (mm)	R^2
19/01/1996	15	11	440	1.10	0.63
04/05/1996	25	5	67	1.40	0.03*
30/08/1996	100	16	50	1.56	0.76
06/12/1996	8	5	620	0.27	0.95
19/12/1997	8	5	390	0.27	0.96
03/01/1998	10	6	300	0.35	0.92
11/11/1998	13	12	268	0.49	0.61

* timing shift of 1 hour between the two rainfall series is likely

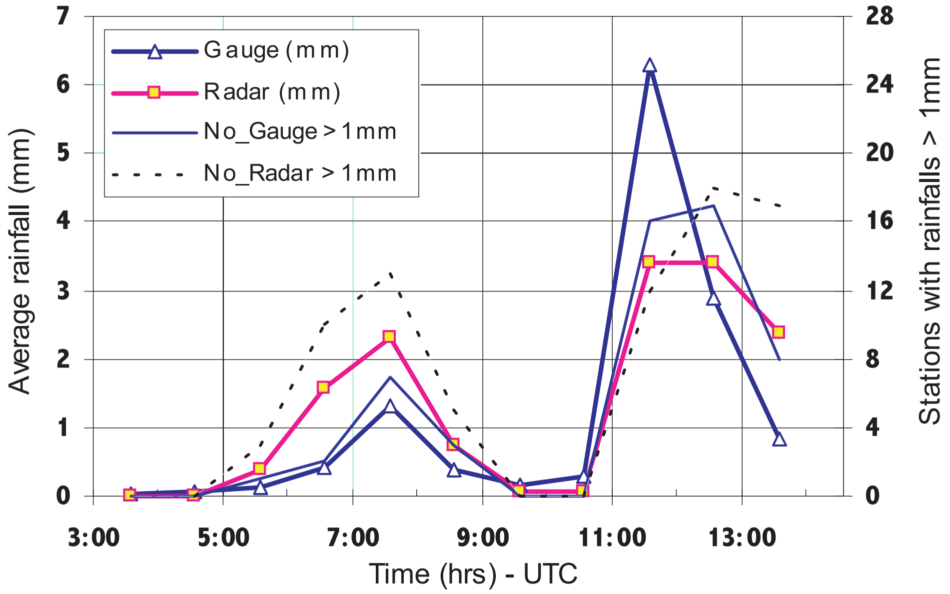

Figure 3.5 Calibration results for 19 January 1996

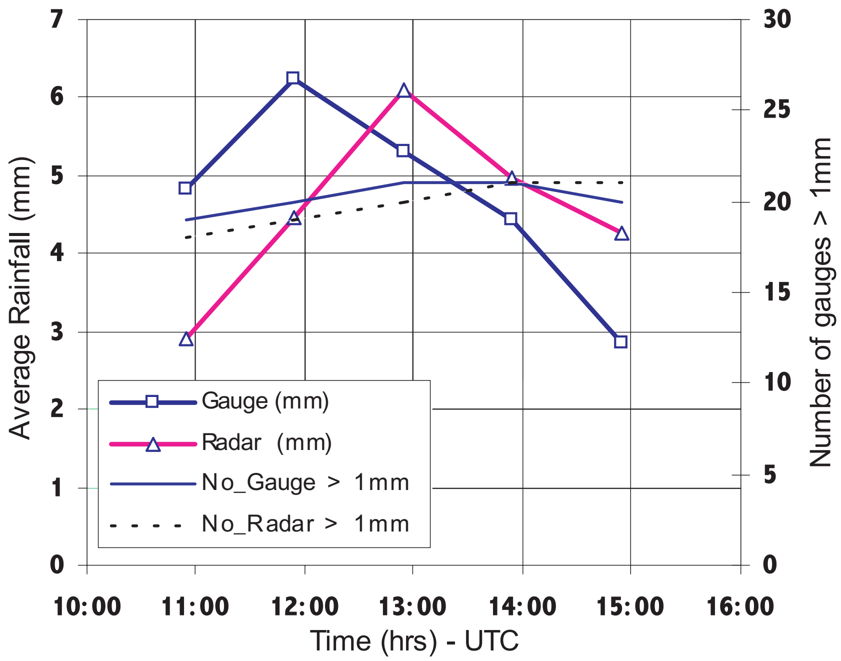

Figure 3.6 Calibration results for 4 May 1996

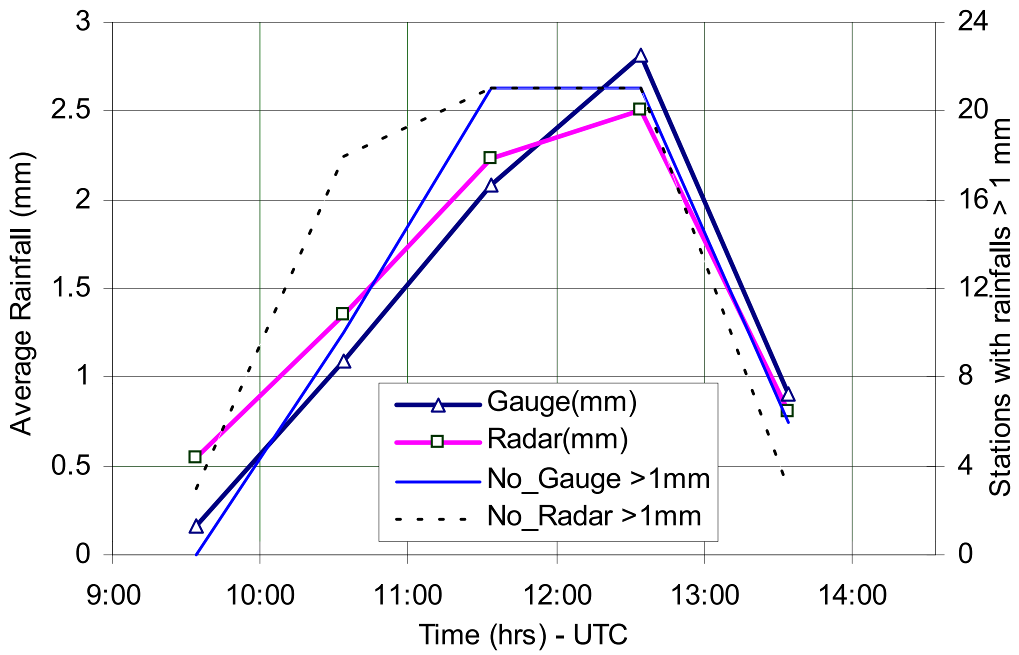

Figure 3.7 Calibration results for 30 August 1996

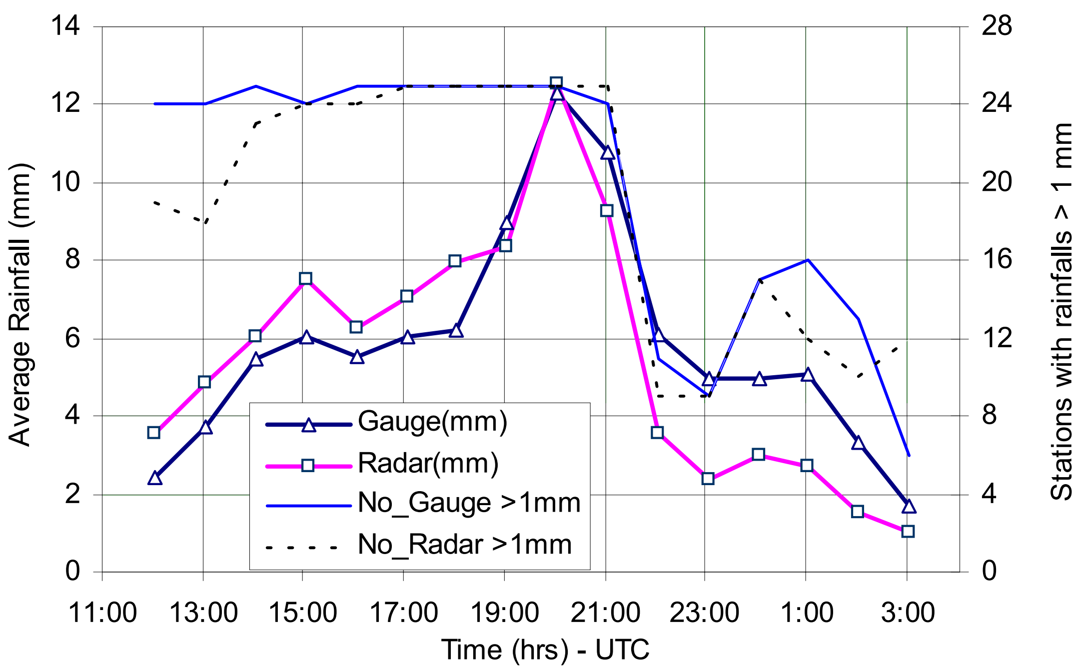

Figure 3.8 Calibration results for 6 December 1996

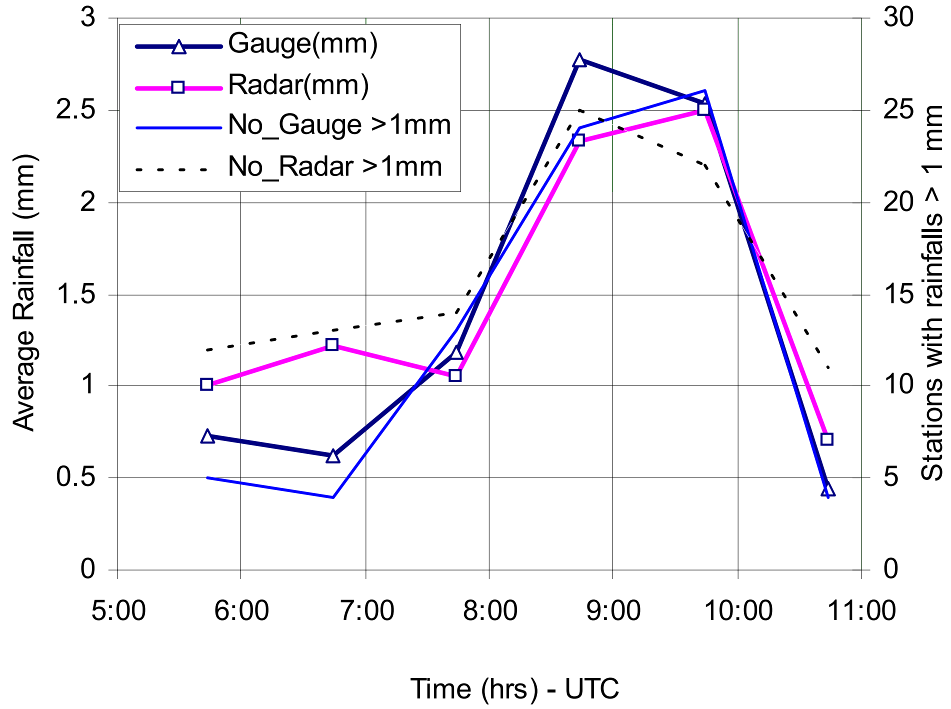

Figure 3.9 Calibration results for 19 December 1997

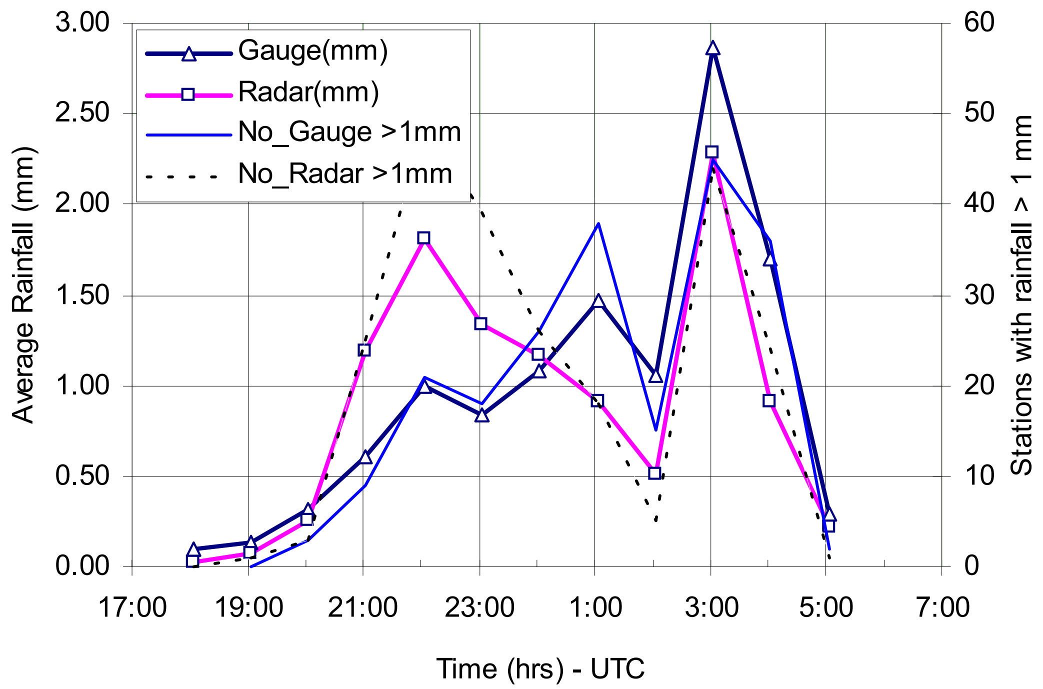

Figure 3.10 Calibration results for 3 January 1998

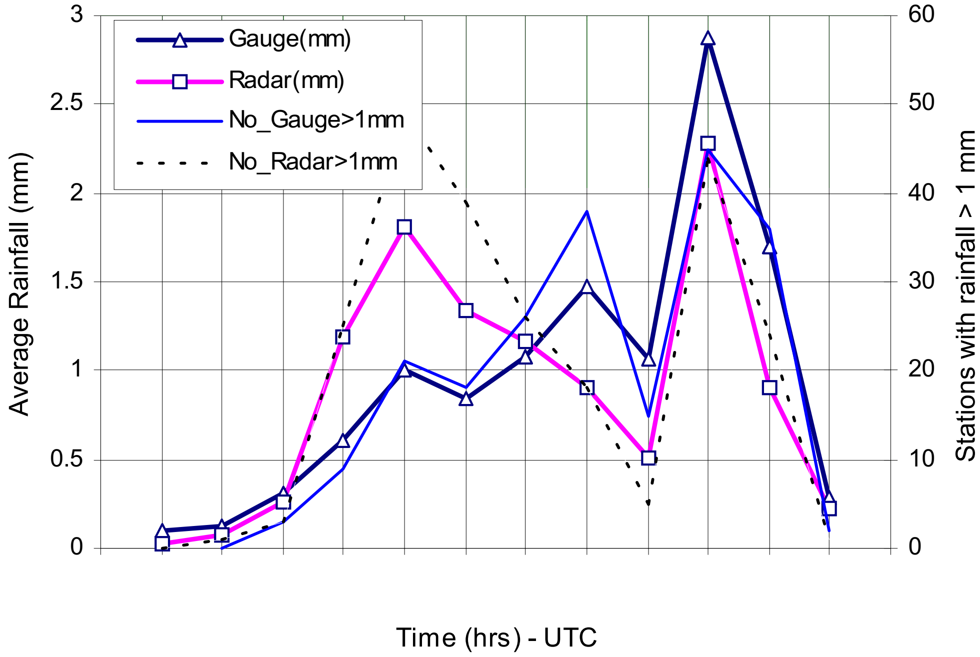

Figure 3.11 Calibration November 1998

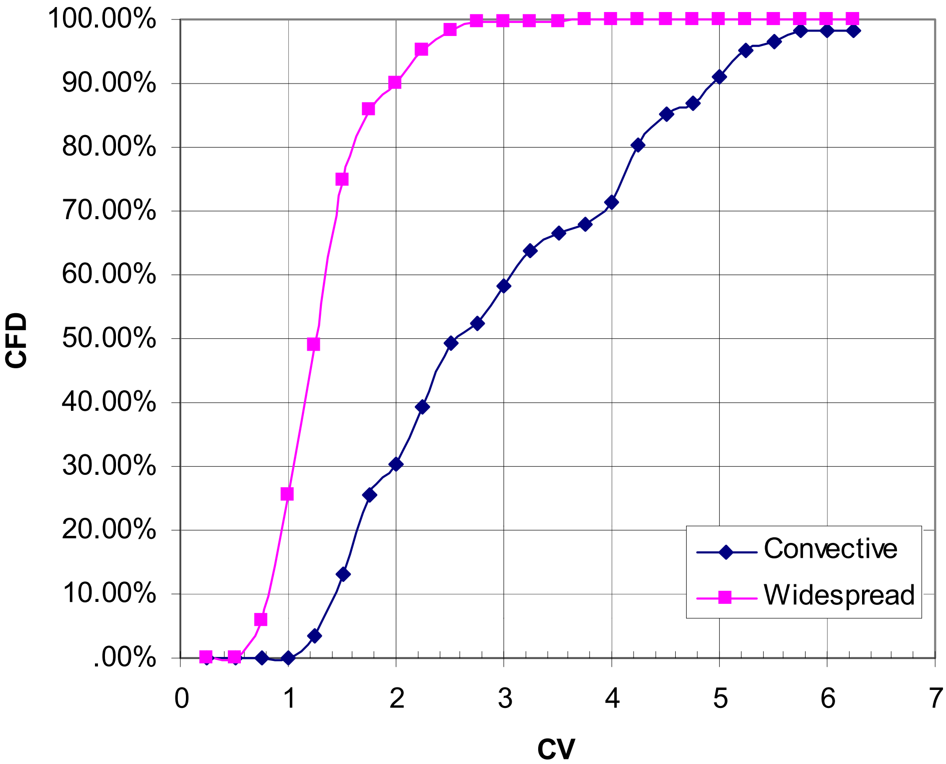

Figure 3.12 Cumulative frequency distribution (CFD) for the CV for “convective” and “widespread” rainfall cases

3.4 Evaluation of Results Against Storm Characteristics

It was shown in Section 3.3.2 that the value of parameter *a* of the *Z-R* relationship ranged from 50 to 620 with an average of 305. It would be worthwhile to investigate whether these differences can be explained through characteristics of the storms analysed.

The storms that occurred on 03/01/1998, 19/12/1997 and 19/01/1996 were scattered and can be considered as convective storms. The rest of the storms were more widespread and can generally be considered as widespread storms associated with low-pressure systems, or convective cells embedded within more widespread rainfall. In particular, the event on 30/08/1996 was an example of an East Coast Low producing widespread rainfall with rainfalls totalling up to about 150 mm.

In Chapter 2, it was found that the climatological value of $a = 280$, with $b = 1.6$, is suitable for representing all types of storms in the Sydney area. The three scattered storms identified as convective have calibrated *a* values of 300, 390 and 440. When these three storms were integrated and re-calibrated as a single combined storm, the analysis yielded a value of $a = 400$.

Calibrated values for the other four widespread storms were a = 67, 50, 620, and 268 for 04/05/1996, 30/08/1996, 06/12/1996, and 11/11/1998 respectively. The two events with on-shore easterly to northeasterly winds (04/05/1996, 30/08/1996) have a = 67 and 50 respectively, the low value possibly a result of an underestimation of the radar rainfall due to orographic enhancement. The two cases with offshore westerly to northwesterly winds (06/12/1996 and 11/11/1998) occurred during the summer months and have values of a = 620 and 268 respectively. For these storms radar reflectivity measurements were consistently higher in comparison to the lower rainfalls recorded at gauging stations, possibly as a result of evaporation of raindrops from the radar measurement to the ground (06/12/1996) or of the presence of convective showers towards the end of the event (11/11/1998). This group of (so-called) widespread storms was therefore further classified on the basis of the predominant wind direction, with the *Z-R* relation $Z = 60R^{1.6}$ being classified as the "East Coast Low" relationship rather than the "widespread" *Z-R*.

This analysis suggests three possible classifications; firstly the convective storms then, within those generally classified as widespread, a separation of those caused by an East Coast Low from those with a more westerly offshore wind flow can be made. It would be useful to have some objective method for classifying events among these three variations. The coefficient of variation (*CV* = the ratio of the standard deviation to the mean) of the spatial distribution of rainfall can be considered to be a measure of the relative variability of the rainfield. The *CV* was calculated for each 10-minute rainfield in the data set and the cumulative frequency distribution was calculated for the combined convective and widespread cases as shown in Figure 3.12. The classification rule: widespread rainfall if $CV < 2.0$, convective rainfall otherwise, will classify 70% of the convective cases and 90% of the widespread cases correctly.

Having used this approach to objectively separate out the widespread rainfall cases ($CV<2$), the East Coast Low case can be assigned to those widespread cases that have an easterly advection component. It is worth doing this because rainbands associated with East Coast Lows generate significant widespread rainfall in the Sydney area and are responsible for large regional floods on the East Coast. The climatological *Z-R* relationship will underestimate the rainfall intensities by a factor of about three during these events, therefore it is important to at least identify the East Coast Low situations and then use the appropriate *Z-R* relationship.

With regard to the remaining classifications, it should be noted that the differences between rain rates derived using a = 280 and 400 are generally less than 20% for rain rates less than 20 mm h^{-1}. This is of the same order of magnitude as the noise in a *Z-R* calibration analysis and therefore it is difficult to differentiate between these two cases (convective and non-East Coast Low widespread rainfalls). Therefore, the climatological *Z-R* relationship ($Z = 280R^{1.6}$) could be used as default for any event that is not an East Coast Low type of event.

4. Event calibration for Melbourne

This chapter describes the calibration of radar rainfall data for Melbourne area using hourly gauged rainfall data using a similar approach to that used in Sydney in Chapter 3.

4.1 Data for calibration of *Z-R* relationship

4.1.1 Radar data

Radar images were obtained from Laverton radar station located about 20 km West of Melbourne. Four of the most significant 24-hour storms in the record (26/12/1993, 10/02/1994, 02/03/1999 and 26/12/1999) were selected from the radar archive as case studies. Details of each event are summarised in Table 4.1 and spatial patterns of accumulated rainfall are shown in Figures 4.1 to 4.4 for the four case studies.

4.1.2 Raingauge Data

The hourly rainfall data were obtained from pluviograph stations maintained by Melbourne Water. It should be noted that most of the stations are concentrated around Greater Melbourne and surrounding areas and only a few stations represent those parts of country Victorian

Table 4.1 Details of the rainfall events used in Melbourne.

Date	Duration (h)	Depth (mm)	Description
26/12/1993	24	51	Widespread rainfall associated with a cut-off low
10/02/1994	24	56	Widespread rainfall associated with prefrontal trough
02/03/1999	9	16	Convective cells embedded in a frontal rainband
26/12/1999	60	78	Long sequence of convective storms

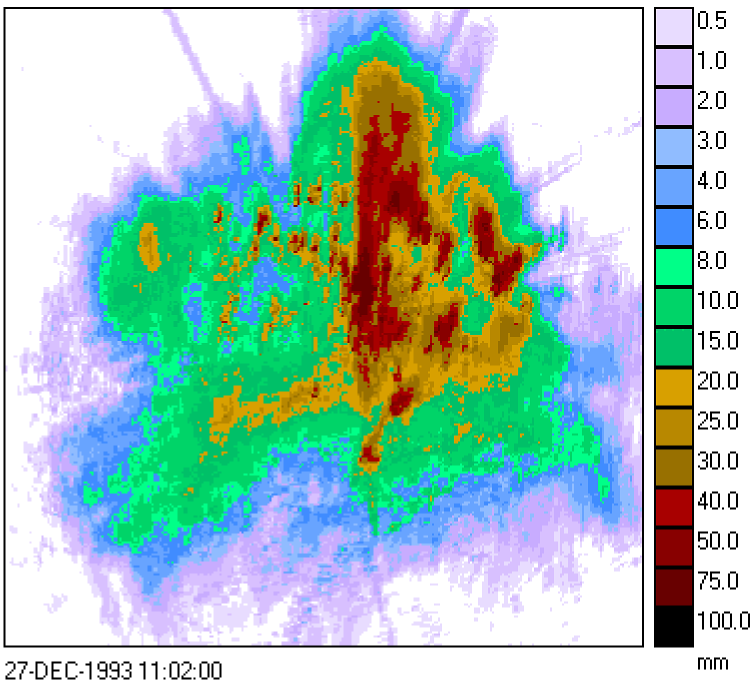

Figure 4.1 12-hour accumulation of rainfall ending 11:02 UTC 27 December 1993. The radar at Laverton is at the centre of the image, which is a square with 256 km sides, 1 km resolution

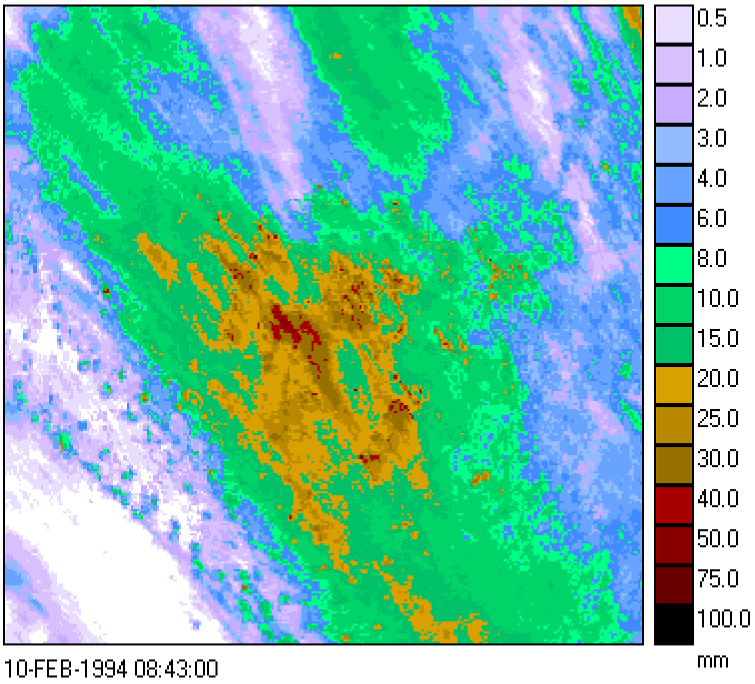

Figure 4.2 12-hour accumulation ending 08:43 UTC 10 February 1994. The radar at Laverton is at the centre of the image, which is a square with 256 km sides, 1 km resolution

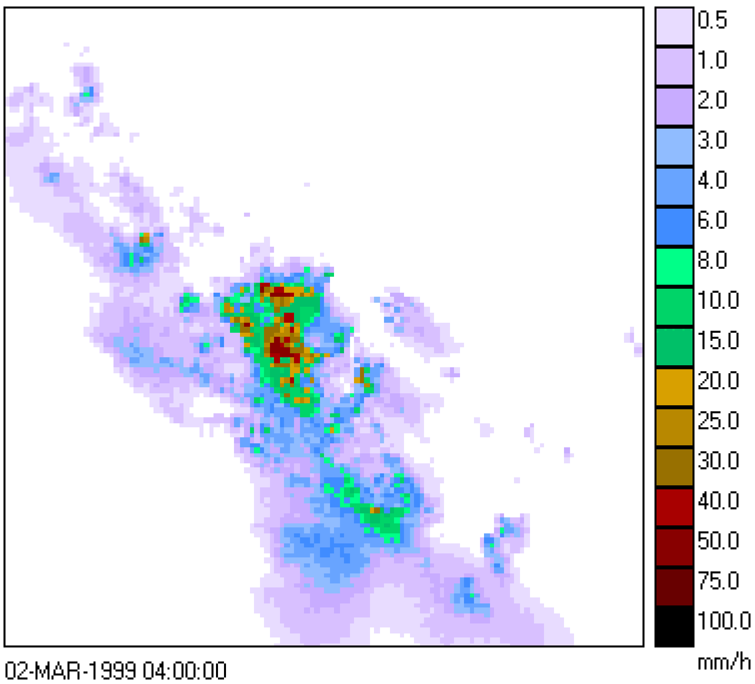

Figure 4.3 1-hour accumulation ending 04:00 UTC 2 March 1999. The radar at Laverton is at the centre of the image, which is a square with 256 km sides, 1 km resolution

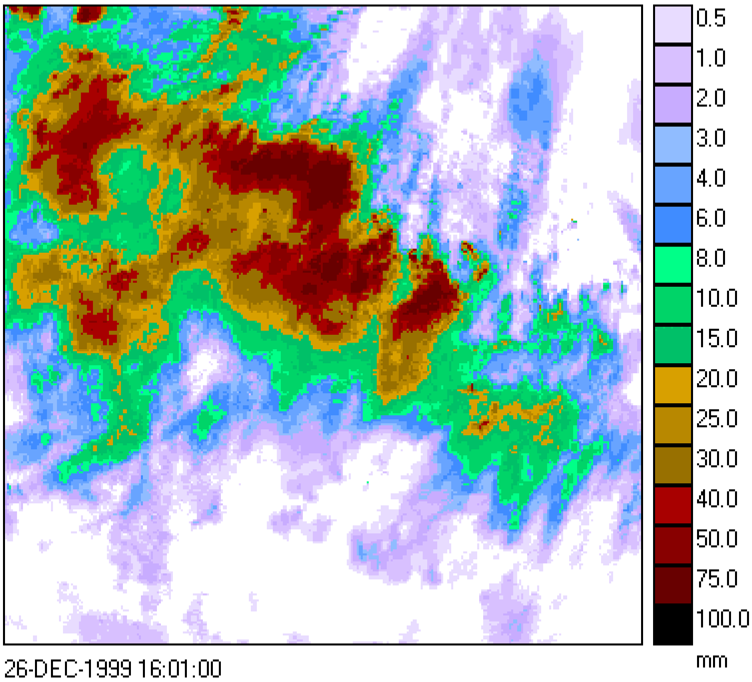

Figure 4.4 12-hour accumulation ending at 16:01 GMT 26 December 1999. The radar at Laverton is at the centre of the image, which is a square with 256 km sides, 1 km resolution

regions that are within radar coverage. The rainfall records were checked for consistency and a few stations whose records show clear inconsistencies with those of nearby stations were eliminated from the study. A total of 77 suitable stations were used to calibrate the 2 March 1999 case and the other three cases were calibrated using 45 stations.

4.2 Results

In Chapter 2 the climatological *Z-R* relationship for the Melbourne area was estimated to be $Z=75R^{1.6}$. The parameters of this relationship were taken as preliminary parameter values and used to derive the preliminary radar rainfall fields. The parameter *a* was then calculated such that the RMSE between the gauged rainfalls and the arithmetically averaged hourly radar rainfalls at the same locations was minimised. The results are summarised in Table 4.2 and the time series of hourly average rainfalls compared in Figures 4.5 to 4.8.

The reasons for the poor performance of the radar/ raingauge inter comparison for the 26 December 1999 event can be found in the spatial variability and intermittency of the rain fields for this case. Figure 4.9 shows a close-up of the 1-hour rainfall accumulation field ending at 06:00 UTC 27 December 1999 together with the Melbourne Water raingauge network. The brown colours in the image represent rain rates that are greater than 40 mm h^{-1}. It can be seen from this figure that the rainfall missed most of the gauges which has resulted in significant differences between the mean radar and mean raingauge rainfall.

Generally, the radar can be expected to produce estimates of hourly mean areal rainfall that are within 1 mm h^{-1} of that measured by a (dense) gauge network.

Table 4.2 Estimated value of *a*, given than *b* = 1.6, for the four Melbourne events. The *RMSE* is calculated using the hourly time series of mean areal rainfall based on the gauge and radar measurements

Date	***a***	***RMSE* (mm h^{-1})**	**r^2**
26/12/1993	52	0.8	0.61
10/02/1995	98	1.2	0.54
02 /03/1999	70	0.2	0.97
26/12/1999	50	1.3	0.04

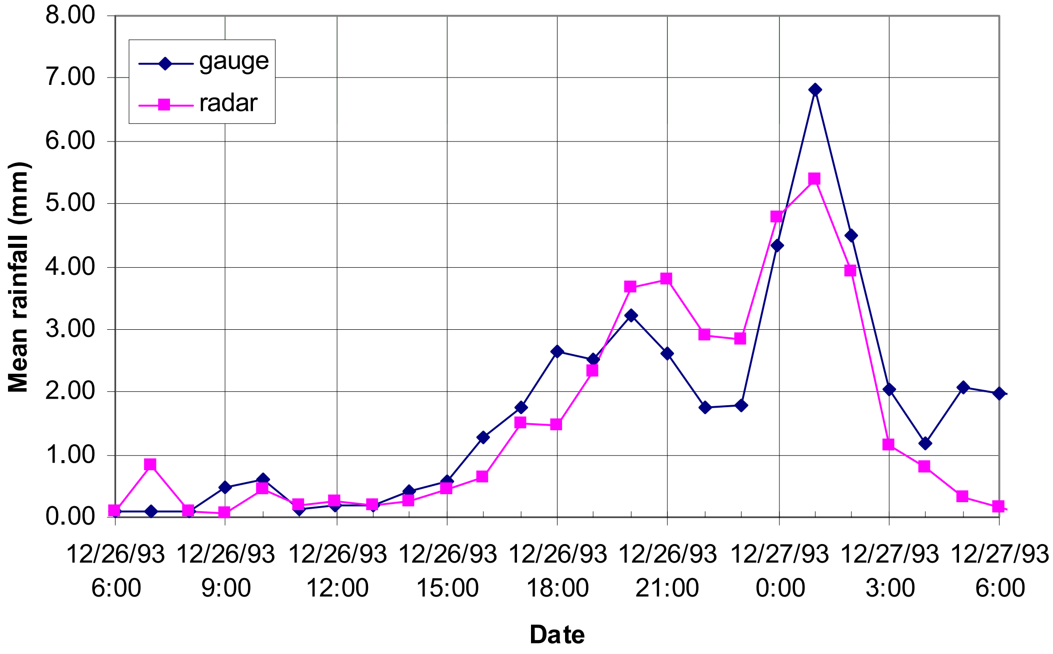

Figure 4.5 Calibration results for 26 December 1993

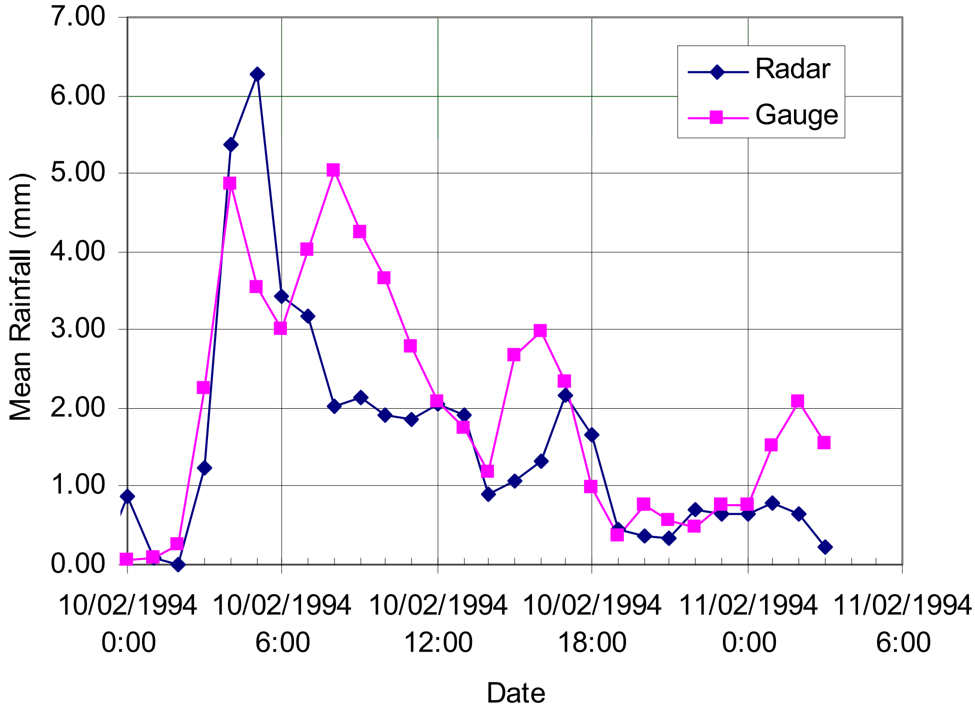

Figure 4.6 Calibration results for 10 February 1994

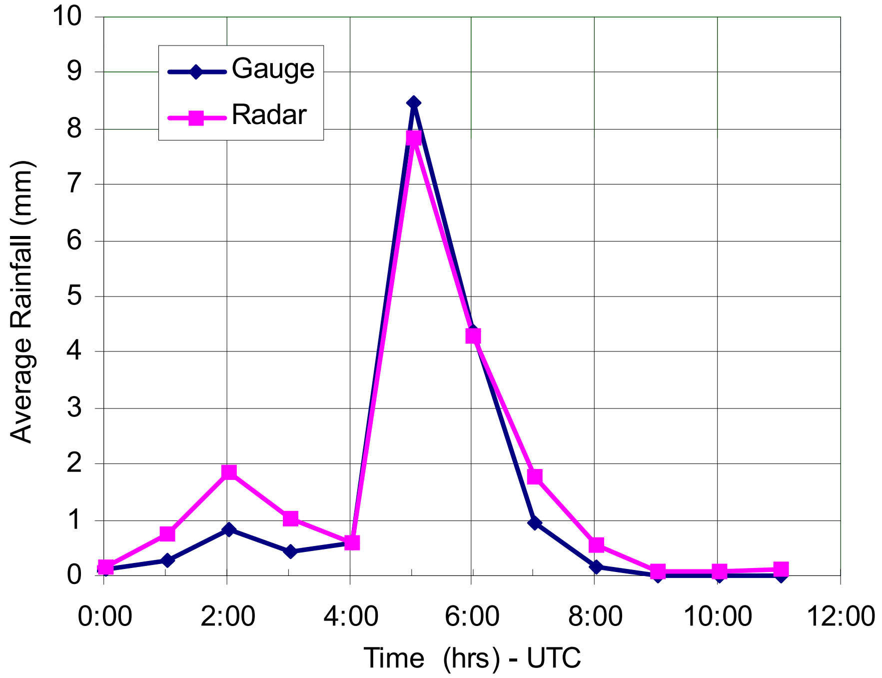

Figure 4.7 Calibration results for 2 March 1999

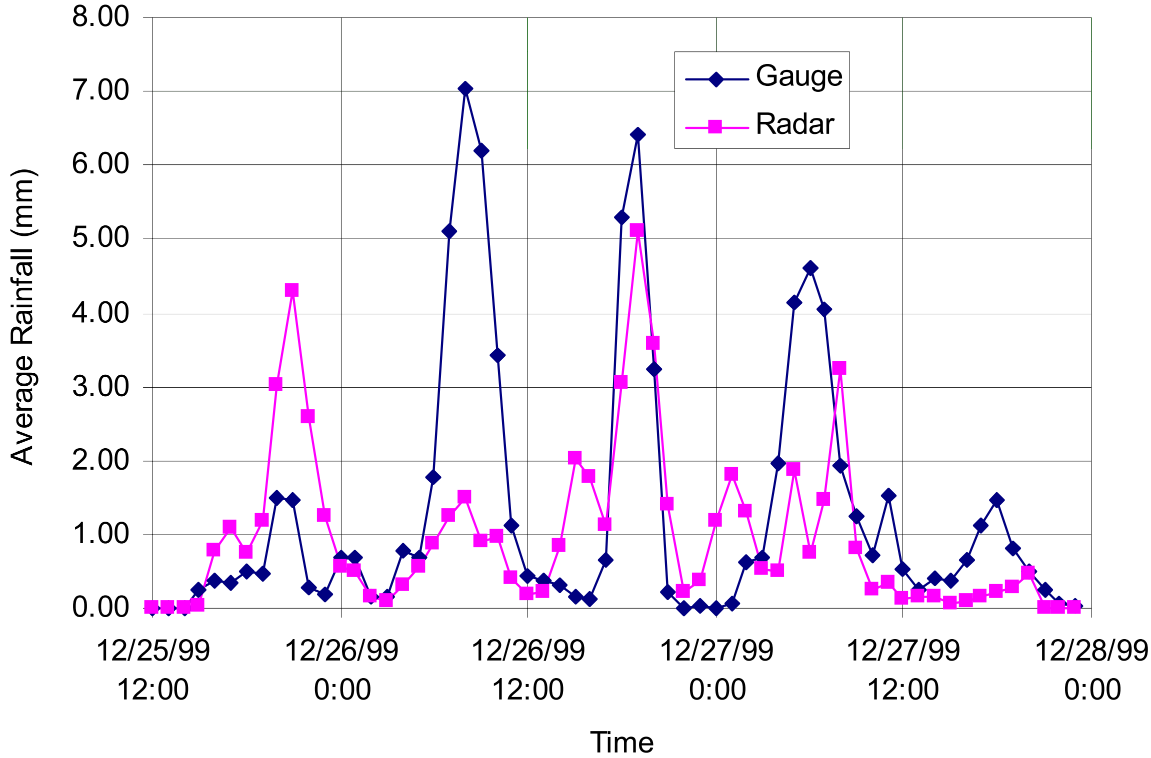

Figure 4.8 Calibration results for 26 December 1999.

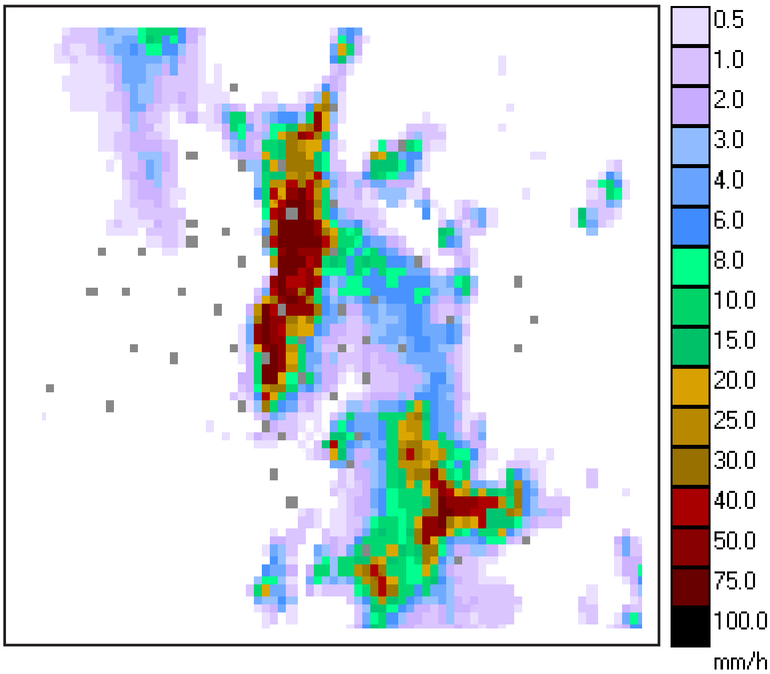

Figure 4.9 A close-up of the 1-hour radar rainfall accumulation field ending 06:00 UTC 27 December 1999, with the Melbourne Water raingauge network marked as grey squares.

5. Conclusions

The expected or climatological *Z-R* relationships for the Melbourne, Sydney, and Darwin weather radars were estimated using gauge and radar estimates of mean areal daily rainfall for between 400 and 600 days for each radar. The results show that a climatological *Z-R* relationship has a root mean square error (RMSE) of about 3-4 mm for daily rainfall accumulations in Sydney and Melbourne and 7-8 mm for Darwin where the mean rainfall is higher. This implies that approximately 30% of the rain days will have errors that exceed these values. Some of the observed error is due to missing data in the radar data set so these errors are likely to be conservative. The climatological *Z-R* relationship $Z = 75R^{1.6}$ for Melbourne is quite unusual since a relationship closer to the standard Marshall-Palmer $Z = 200R^{1.6}$ is expected for Melbourne's climate, and possibly points to unaccounted power losses in the radar system. A comparison of daily gauge data with accumulations of radar data at the same location showed that there were significant differences between point radar and gauge data even for daily accumulations. Some of these differences could be due to missing data in the radar record, but nevertheless, the differences are significant and point to the difficulty in using the radar for point measurements as well as the difficulty in using a single gauge to make local adjustments to the radar field.

An analysis of some widespread rainfall days in Sydney showed that using a climatological *Z-R* in these cases leads to under-estimation of rainfall intensity by a factor of two. Therefore events that cause regional flooding are likely to be underestimated through the use of the climatological *Z-R* relationship. There are two possible approaches to ameliorate this problem, viz. on-line calibration using hourly rainfall accumulations, or the use of an appropriate *Z-R* relationship that depends on the synoptic classification. The latter approach was investigated and led to a decision rule that uses the coefficient of variation (*CV*) to categorise the types of rainfall. The decision rule: East Coast Low rainfall if the coefficient of variation *(CV)* < 2.0 ($Z = 60R^{1.6}$); convective rainfall otherwise ($Z = 280R^{1.6}$) was able to classify 70% of the convective and 90% of the East Coast Low rainfall fields correctly. A simpler alternative is to allow the user to select the appropriate *Z-R* relationship based on their classification of the current situation.

It is evident from this study that the *RMSE* is quite insensitive to the value of the exponent b in the *Z-R* relationship, provided that the multiplier a is adjusted accordingly. This is in keeping with the results from other studies, so the pragmatic strategy of fixing b according to the climate (say b = 1.2 for tropical sites, 1.6 otherwise) and adjusting a accordingly has considerable merit given the noise in the gauge to radar data comparison. The *RMSE* for mean areal hourly rainfall was found to be generally in the 1-3 mm/h range, tending to increase somewhat with increased mean rainfall. This means that the relative performance of the radar in light rainfall situations is very poor indeed, but errors (strictly they are merely differences between the gauge and radar since both have significant measurement errors for mean areal rainfall) of the order of 25% of the mean hourly rainfall are possible during significant events.

Raingauges are quite expensive to install and run, with on-going costs being of the order of $1000 per year for telemetered gauges, and therefore there is reason to minimise the number of gauges that are operated as ground truth for a radar installation. If on-line gauge adjustment is to be effective, errors in the estimation of mean areal rainfall from the ground truth must be significantly less than the errors that arise from using a climatological *Z-R* relationship. The U.K. Met Office reports a *RMSE* of about 2.0-2.5 mm/h for a climatological *Z-R* relationship after extensive quality control. The RMSE for daily accumulations of radar data using a climatological *Z-R* relationship is in the range of 3-4 mm/day for Melbourne and Sydney, compared with the mean conditional daily gauge rainfall of 4.5 mm and 8.7 mm, respectively. Therefore the raingauge network must be able to measure the daily mean areal rainfall to better than around 50% accuracy if it is to be used as ground truth for a radar. A rough guide would be that a minimum network of say 15-20 gauges is required for effective climatological and event calibration, and 30-50 gauges for hourly on-line adjustment.

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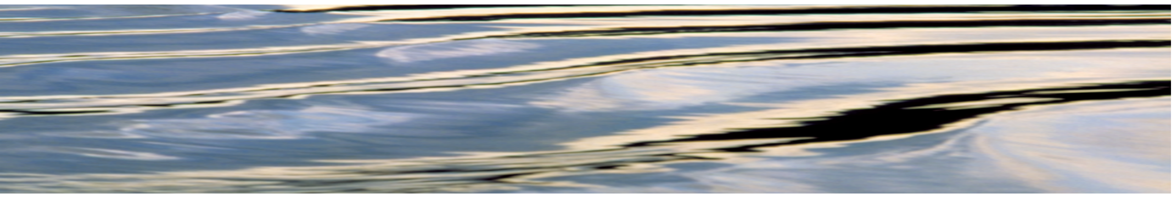

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