Effect of Storm Types in Radar Rainfall Estimates

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Abstract: Radar rainfall is estimated by converting radar reflectivity (Z) into rainfall intensity (R) using an appropriate Z-R relationship. Even if there is no error in the measurement of either reflectivity or rainfall intensity, there is variability in the Z-R relation due to variability in the distribution of rainfall drop size caused by the effect of different storm types. This paper presents a storm classification method for partitioning of radar reflectivity into convective and stratiform components. The proposed classification criteria are derived by investigating the relationship between hourly spatial rainfield statistics and rainfall types. The hourly vertical reflectivity profiles that are derived from the three-dimension structure of the reflectivity field and the hourly radar images are used to validate the proposed criteria. We have found that 70% of the hourly rainfields were classified correctly when using the proposed classification method. The radar rainfall calibrations for convective and stratiform rainfall are performed separately. A 6-month long radar and rain gauge rainfall that occurred across Sydney, Australia between November 2000 and April 2001 are used to illustrate the efficiency and applicability of applying the proposed storm classification method in radar rainfall estimation, compared to radar rainfall algorithm used conventionally. The result shows that using of the proposed storm classification method in radar rainfall estimation helps to improve the accuracy of radar rainfall by 13% and 11% for the calibration and cross-validation, respectively.

Keywords: *radar rainfall, storm classification, Z-R error*

1. INTRODUCTION

The accuracy of any hydrological model relies on a good spatial and temporal estimate of the rainfall field. Weather radar is a promising tool to improve hydrological modelling and applications as it has a high potential to provide a description of the rainfall field at a fine spatial and temporal resolution. As radars do not measure rainfall directly, it is affected by many sources of error, thereby high uncertainty remains in radar rainfall estimates. Traditionally radar rainfall is derived by converting a measured radar reflectivity *(Z)* into rainfall intensity *(R)* using an appropriate Z-R relationship. The Z-R relationship is often represented by a power law model of the form; $Z = AR^b$ where A and b are model parameters which depend on the rainfall raindrop size distributions that have been sampled and the terminal velocity of the raindrops as a function of their diameter. These parameters can be estimated empirically using measurements of Z and R, or derived from a parameterisation of the raindrop size distribution.

To increase the accuracy of radar measurements of rainfall, two broad classes of errors need to be taken into account (Seed et al., 2001). These are (1) reflectivity measurement errors; and (2) conversion of reflectivity to rainfall rate errors.

Errors in measured radar reflectivity are caused by temporal and spatial sampling error, height sampling error leading to range dependent bias, ground clutter, anomalous propagation, beam blocking, beam attenuation, electrical calibration error and quantisation of reflectivity error. The previous studies have shown the interest of taking into account the accuracy of a measured reflectivity while dealing with the correction procedures for rainfall estimation from radar measurement. The Z-R conversion error can be substantially reduced if the parameter of Z-R relationship has been estimated from the data that have the same characteristic of rain type and same geographic location (Austin, 1987).

Differences between raindrop size distributions of convective and stratiform rain will cause the Z-R parameters of these two rainfall types to be significantly different (Atlas et al., 1999). Using a single Z-R relation to estimate radar rainfall will lead to a high uncertainty in radar rainfall estimates. Hence, the reflectivity values need to be discriminated into convective and stratiform rain and the *Z-R* relation of each rain type should be used in estimating the radar rainfall.

This paper attempts to reduce the *Z-R* conversion error in radar rainfall estimates. We propose a storm classification method for partitioning of hourly radar reflectivity into convective and stratiform components. The proposed classification criteria are derived by investigating the relationship between hourly spatial rainfield statistics and rainfall types.

It is to be mentioned that the proposed storm classification method can not be used to classify the spatial variability of storm types within an hour. However, it can be considered for use in estimating the climatological *Z-R* parameters of convective and stratiform rainfall, which are required for estimating radar rainfall of convective and stratiform components after the spatial storm classification (e.g., Steiner et al., 1995) has been performed.

2. PHYSICAL DIFFERENCE BETWEEN STRATIFORM AND CONVECTIVE PRECIPITATION

The physical mechanism of stratiform and convective precipitation is significantly different. Stratiform precipitation usually falls from the anvils of extensive convective cloud systems, which are characterized by light to moderate precipitation rates, weak horizontal reflectivity gradients, and the existence of a radar bright band near the melting layer (Houze, 1993). In general, radar reflectivity in the bright band region is stronger than in rain below or the snow directly above about 5-10 dBZ as illustrated in Figure 1a.

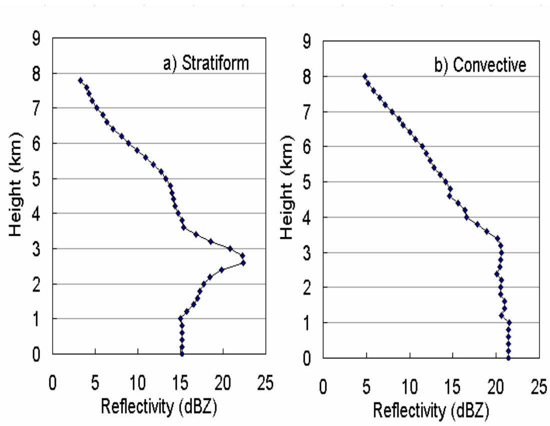

Figure 1. Vertical profile of stratiform (22 Apr 01) and convective reflectivity (30 Jan 01).

Convective precipitation process is contrast sharply from stratiform process (Steiner et al., 1995). The vertical air motion of this type of precipitation is equal or higher than the fall speeds of the precipitation particle. The air motion in a state of convection is usually characterized by strong up and down drafts. Radar echoes associated with strong convective updraft cores, in which large concentrations of droplets condense rapidly and are readily available for collection by larger precipitation particles, form well-defined vertical cores of maximum reflectivity (as illustrated in Figure 1b), which contrast markedly with the horizontal orientation of the radar bright band seen at the melting layer in stratiform precipitation. The intensity of convective precipitation exhibits strong variability in the horizontal more than that of stratiform precipitation.

The distinction of the horizontal and vertical radar reflectivity structures of the convective and stratiform rainfall will be used to discriminating between these two types of rainfall.

3. EXISTING STORM CLASSIFICATION METHODS

There have been numerous methods devised to partition the rainfall from precipitation clouds into convective and stratiform components. Many of these originate from studies of rain gauge data by applying simple threshold methods to rain gauge rainfall (Austin and Houze, 1972) to distinguish between the two rainfall types. Convective classification was assigned whenever the rain rate exceeded some background level by a certain threshold (background-exceedence technique, BET). This method generally identifies the core of the convective rain. The BET method has been extended to the two-dimension radar reflectivity by Churchill and Houze (1984). They assigned a fixed radius of influence to each identified convective core. The radius was assigned as convective zone. The cloud top temperature observed by the satellite has also been used to denote the location of convective (Alder and Negri, 1988). The infrared brightness temperature of the core was used to identify the radius of influence of each core (Adler and Mack, 1984). Steiner et al. (1995) considered that the fix convective radius as proposed by Churchill and Houze (1984) was insufficient, therefore they proposed a rain classification method using two-dimension radar reflectivity by varying the size of convective radius of influence around each core. Yuter and Houze (1996) found that, separation of *Z-R* relations for convective and stratiform precipitation are not justified, and techniques to distinguish between convective and stratiform precipitation based solely on the characteristics of drop size distributions are not likely to be accurate. However, the study of Atlas et al. (1999) shown that the characteristics of the raindrop size distribution are remarkably consistent within each classification. They concluded that partitioning of rainfall into a sequence of types could be achieved by classification based on the behavior of the representative drop size (median volume diameter of raindrops) and rain rate.

In general, the raindrop size distributions vary in space and time, leading to spatial and temporal variability of the *Z-R* relationship. This implies that the storm classification methods should be capable of recognizing such temporal and spatial changes in the *Z-R* relationship. As the raindrop size distribution data are usually not available for use to validating the classification method, hence the vertical profile of reflectivity (VPR) will be used instead. Therefore, the accuracy of the classification of each pixel is still susceptible, since there is high uncertainty in calculating of VPR of each pixel, especially for the pixels located far from the radar as the accuracy of VPR reduces with range due to the widening of the radar beam.

The *Z-R* parameters of the convective/stratiform rain are estimated by calibrating hourly convective/stratiform reflectivity data with hourly rain gauge rainfall. Hourly reflectivity values are obtained by accumulating the instantaneous reflectivity that fall with an hour. Hence uncertainty in rainfall type within each hourly time step remains, even though the temporal and spatial storm classification methods have been used.

In this paper, we present a simple hourly storm classification method, which aims to estimate the climatological convective and stratiform parameters of the *Z-R* relationship and use the estimated parameters in estimating of radar rainfall in order to reduce the *Z-R* conversion error.

4. PROPOSED HOURLY STORM CLASSIFICATION METHOD

The horizontal structure of stratiform rainfield is more uniform than convective rain. The proposed hourly storm classification method is based on the uniform observed in the horizontal structure of the incident rainfield. The spatial rainfield statistics that can be considered to be a measured of relative variability of the rainfield will be used as the classification parameters. The coefficient of variation (*CV*) can be used to measure the variability of rainfield relative to the magnitude of the population mean, hence the first classification parameter is the *CV* of an hourly rainfield. The other way of investigating spatial correlation in a field is to examine the spatial power spectrum, which shows the contribution of fluctuations in the field at various scales to the total observed variance of the field. The slope of power spectra, β , indicates the nature of spatial correlation within the fields. The spatial correlation of the field can also be investigated by using a variogram. In general, the variogram is suitable for measuring the spatial correlation of the small scale field. Since it is difficult to differentiate the spatial correlation of convective and stratiform rain within a small scale rainfield, therefore the spatial correlation of the large scale field will be considered instead. The β can be used to measure the spatial correlation of the large scale field, hence we consider to use the β as a second classification parameter to measured the spatial correlation within the 32 km – 170 km rainfield scale. To avoid misclassification of the light showers as convective rain, we also introduce the hourly conditional mean rainfall rate as a third classification parameter.

The classification criteria were investigated based on the 1.5 CAPPI (Constant Altitude Plan Position Indicator) reflectivity data of the three significant rainfall events (30 Jan 01, 22 Apr 01 and 5 May 01). The proposed classification criteria were derived as follows:

a). Calculate rainfall field by using the climatological *Z-R* parameter (A=125, b = 1.5).

b). Calculate hourly VPRs from the three-dimension volume scans. Note that, since the radar rainfall error variance can be considered to be independent with range at the range less than 55 km from the radar (Chumchean et al., 2003), the hourly VPRs were estimated by averaging reflectivity of the radar pixels that lie within that range.

c). Investigate the relationship between the three classification parameters and rainfall types. The hourly VPRs and hourly radar images were used to identify the type of rain for each hour. We consider that if the bright-band is strongly present in the VPR then we classify that hour to be stratiform otherwise convective. In some situations where the presence of bright-band is weak (i.e. about 1-2 dB), the hourly spatial rainfield that can be seen from the radar images are used to select the type of rain for that hour.

d). Adjust the classification parameters that obtained from step c) by optimising the R^2 of the climatological radar rainfall estimation. Note that The R^2 statistic is used as a dimensionless measure of model accuracy in the results presented. It is estimated as:

$$R^2 = 1 - \frac{\sum_{i=1}^{N_t}\sum_{j=1}^{N_g}(R_g - R_r)^2}{\sum_{i=1}^{N_t}\sum_{j=1}^{N_g}(R_g - \overline{R}_g)^2} \quad (1)$$

where R_g is the rain gauge accumulation at the jth gauge, R_r is the radar accumulation around this gauge, both for the ith time period, N_g is the number of rain gauges, N_t is the number of time periods and $\overline{R}_g$ is the mean of rain gauge rainfall. By following the above steps, finally the classification criterion for convective rainfall is as follows:

$$\begin{bmatrix} CV > 2.4 \\ \beta < 2.7 \\ \text{Conditional Mean Rainfall} > 4\ \text{mm/hour} \end{bmatrix},$$

with the rainfall being classified as stratiform if either of the above conditions are not satisfied.

It is to be noted that the three classification parameters were investigated based on hourly rainfield statistics instead the reflectivity field as the magnitude of noise in the reflectivity field is much higher than the rainfall field. The hourly rainfall was estimated by converting hourly reflectivity into rainfall rate using the climatological *Z-R* parameter. The proposed classification criteria were used to classify the three events (124 hours) into convective and stratiform components. The means of the hourly CV, β, and conditional mean rainfall rate of these three events are 2.6, 2.2 and 3 mm/h for stratiform and 3.9, 1.8 and 4.3 mm/h for convective components. The mean of the power spectra at different scales (frequency) of convective and straitiform rain of the three events is shown in Figure 2. The β value of stratiform rain is higher than convective rain due to a higher spatial correlation within the large scale rainfield of the stratiform rain.

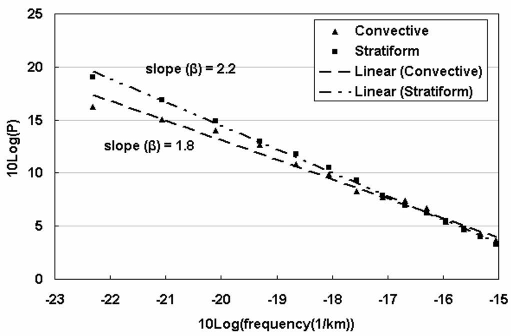

Figure 2. The mean of spatial power spectrum of convective and stratiform components of the three events.

The proposed classification criteria were validated using the hourly VPRs and the radar images of the three events. We have found that the accuracy of the proposed classification criteria is about 70% when validated with the hourly VPRs and the radar images of the three events.

5. APPLICATION TO THE KURNELL RADAR

The 6-month (Nov 00 - April 01) 1.5 km CAPPI reflectivity data record from the Kurnell radar at Sydney and a 254 hourly rain gauges (as illustrated in Figure 3.) that were obtained from tipping bucket rain gauges were used to test the efficiency and applicability of applying the proposed storm classification method in radar rainfall estimation. This type of rain gauge records the time of bucket tips, hence they are subject to significant quantisation error at low rainfall intensity. Therefore, only the rainfall amounts that are greater than the volume of that gauge's tipping bucket were used in this study. The Kurnell radar transmits radiation with a wavelength of 5.3 cm and produces a beam with a 3 dB width of 0.94°. The reflectivity data are in Cartesian grid with 256 km x 256 km extent and a 1 km^2, 10-minute resolution. Hourly reflectivity values were obtained by accumulating the 10-minute reflectivity data that fall within that hour, so that the radar data could be compared with the gauge data. The hourly reflectivity were obtained by converting the snapshot 10-minute reflectivity data to rainfall, applying the accumulation method proposed by Fabry et al. (1994). This method accounts for the movement of the rainfall field between the instantaneous rainfall intensity fields produced by the radar, accumulating them into hourly data and then converting hourly rainfall back into dBZ using the same Z-R relation. The effect of bright band and a different observation altitude at far range are the other sources of error in radar rainfall estimates. In order to avoid the biases caused by these two sources of error, only the measured reflectivity and rain gauge data that lie within 100 km from the radar were used in this study. Note that the climatological freezing level of Sydney area during the study months are above 2.5 km and the height of the base scan beam centre at 100 km from the radar is 1.9 km above the ground which can be considered to be not overly different from 1.5 km. Therefore, we assume that there is no bias caused by the bright band effect and different observation altitude in the 1.5 km CAPPI data that lie within 100 km from the radar. To avoid the effect of noise and false interpretation caused by hail in the measured radar reflectivity, the reflectivity values that are less than 15 dBZ and greater than 53 dBZ (Fulton et al., 1998) were excluded from the analysis.

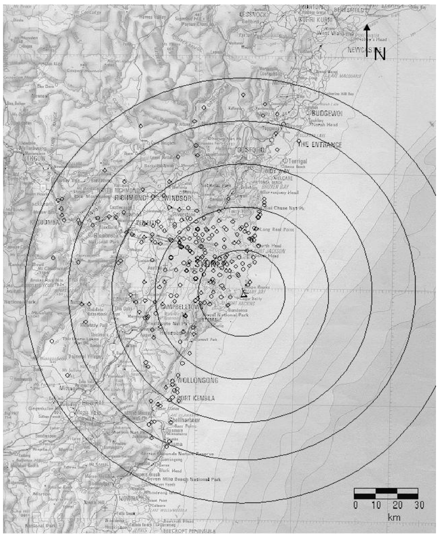

Figure 3. Sydney rain gauge network, the Kurnell radar (radar symbol) and range ringes at 20, 40, 60, 80 and 100 km from the radar.

6. RESULTS AND DISCUSSIONS

The 27 events (819 hours) that occurred during Nov 00 to April 01 were separated into convective and stratiform rain using the proposed hourly classification method. We found that 15% of data were classified to be convective and the rest 85% were classified as stratiform rain. Hourly rain gauge rainfall data were grouped into convective, stratiform and no-classification (combined the entire data set). The conditional mean rain gauge rainfall intensities for the convective and stratiform storm type, along with the intensity when no classification is performed are 6.55, 3.94 and 4.24 mm/h, respectively. This classification result corresponds to the fact that convective rain is expected to have a higher rainfall intensity compared to the others. The conditional mean rainfall rate of the three groups at different range intervals is illustrated in Figure 4.

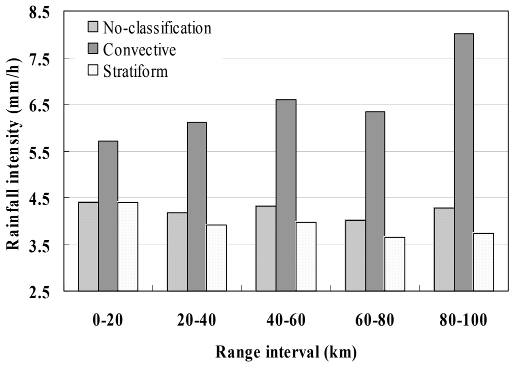

Figure 4. Conditional mean rain gauge rainfall.

From Figure 4, it is interesting to note that the conditional mean convective rain rate at the 80-100 km range interval is much higher than the other ranges. The Blue Mountains and the Southern Highland area are located approximately beyond 80 km west and south-west from the Kurnell radar, respectively. Matthews and Geerts (1994) investigated the characteristic of the thunderstorm distribution in the Sydney area using 959 thunderstorms that occurred during 1965-1989. They found a west to east progression of storms of the Sydney area and reported that the thunderstorms are more common over the Southern Highland and the Blue Mountains around noon, cross the Sydney metropolitan area in the afternoon and stall off-shore at night. Potts et al. (2000) also found that many thunderstorms develop over the mountains, intensify and move east over the coastal plain and decay as they move over the ocean. As most of the thunderstorms that occur in Sydney develop over the mountains, the probability of high convective rainfall intensity is more likely to occur at the range beyond 80 km rather than the other range intervals.

The main aim of this paper is to reduce the *Z-R* conversion error in radar rainfall estimates, hence we integrated the storm classification into the radar rainfall estimation algorithm. The climatological *Z-R* relationship was used to estimate radar rainfall prior to the classification. Eighty five rain gauges that owned and operated by the Bureau of Meteorology were used for calibration and 169 rain gauges that owned and operated by Sydney Water Corporation were used for cross-validation. The analysis was performed in an hourly time step. The "*b*" parameter of the *Z-R* relationship was fixed to 1.5 while the "*A*" parameter was estimated by minimising the Mean Square Error (*MSE*) between rain gauge and radar rainfall estimates. To investigate the accuracy of the radar rainfall estimation algorithms, the R^2 of each rainfall estimation algorithm was measured. The calibration and cross-validation results are presented in Table 1.

Table 1. Calibration and cross validation results

Calibration strategies	"A" parameter	R^2	
		Calibration	Validation
No-classification	125	0.25	0.23
Hourly-classification	232 (74)	0.38	0.34

***(***) = convective (stratiform)

Table 1 shows that the parameter of convective and stratiform rain is significantly different. The "*A*" parameter of convective rain is much higher than stratiform rain, as expected. This is because the drop diameter of convective rain is larger than stratiform, hence the reflectivity values that obtained from convective component are higher than stratiform for the same rainfall rate, as a result that reflectivity is more sensitive to the diameter of raindrop than rainfall rate. We also have found that using of the proposed classification method can improve the accuracy of radar rainfall by 13% and 11% for the calibration and cross-validation, respectively.

7. CONCLUSIONS

The work in this study can be summarized below:

1. We proposed a simple hourly storm classification method by considering the physically meaningful information that distinguishes the horizontal structure of convective and stratiform rainfields.

2. The climatological “*A*” parameter of no-classification, convective and straiform rain is significantly different viz. 125, 232 and 74, respectively.

3. The proposed hourly classification method helps to reduce the *Z-R* conversion error, and consequently improves the accuracy of radar rainfall. The results in this study show that application of hourly storm classification in the parametric *Z-R* relationship can improve the accuracy of radar rainfall by 13% and 11% for the calibration and cross-validation, respectively

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9. REFERENCES

Adler, R.F. and A.J. Negri, A satellite infrared techniques for estimate tropical convective stratiform rainfall, *J. Appl. Meteorol.,* 27, 30-51, 1988.

Adler, R.F. and R.A. Mack, Thunderstorm cloud height-rainfall rate relations for use with satellite rainfall estimation techniques, *J. Climate Appl. Meteorol.,* 23, 280-296, 1984.

Atlas, D., C.W. Ulbrich, F.D. Marks Jr., E. Amitai and C. R. Williams, Systematic variation of drop size and radar-rainfall relation, *J.Geophys. Res.,* 104(D6), 155-6169, 1999.

Austin, P.M. and R.A. Houze Jr., Analysis of the structure of precipition patterns in New England, *J. Appl. Meteorol.,* 11, 926-935, 1972.

Austin, P.M., Relation between measured radar reflectivity and surface rainfall, *Mon. Wea. Rev.,* 115, 1053-1070, 1987.

Chumchean, S., A. Sharma, A. Seed, Radar rainfall error variance and its impact on radar rainfall calibration, *J. Phys. and Chem. Earth,* 28(1-3), 27-39, 2003.

Churchill, D. D., and R.A. Houze Jr., Development and structure of winter monsoon cloud clusters on 10 December 1978, *J. Atmos. Sci.,* 41, 933-960, 1984.

Fabry, F., A. Bellon, M.R. Duncan, G.L. Austin, High resolution rainfall measurements by radar for very small basin: the sampling problem re-examined, *J. Hydrol.,* 116, 415-428, 1994.

Fulton, R.A., J.P. Breidenbach, D.-J. Seo, D.A. Miller, and T. O’Brannon, The WSD-88D rainfall algorithm, *Wea. Forecasting,* 13, 377-395, 1998.

Houze, R.A. Jr., Cloud Dynamic, *Academic Press*, 573 pp, 1993.

Matthews, C., and B. Greets, Characteristic thunderstorm distribution in the Sydney area, *Aust. Meteorol. Mag.,* 44, 127-138, 1995.

Potts, R.J., T.D. Keenan, and P.T. May, Radar characteristics of storms in the Sydney area, *Mon. Wea. Rev.,* 128, 3308-3319, 2000.

Seed, A., L. Sirivardena, X. Sun, P. Jordan and J. Elliott, On the calibration of Australian weather radars, *Technical Report 02/7,* September 2002.

Steiner, M., R.A. Houze and S.E. Yuter, Climatological characterisation of three-dimensional storm structure from operational radar and rain gauge data, *J. Appl. Meteorol.,* 34, 1978-2007, 1995.

Yuter, S.E. and R.A. Houze Jr., Measurements of raindrop size distributions over the pacific warm pool and implications for Z-R relations, *J. Appl. Meteorol.,* 36, 847-867, 1996.