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Study of Rain-Cloud Characteristics Using Weather Radar Data

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Abstract: Understanding of detail structure and behavior of natural rainfall field is important for improving an efficiency of rainmaking activities. The use of data from weather radar is an efficient way of observing rainfall characteristics. Weather radar can measure physical characteristics of rain-cloud such as rain drop size distributions, spatial and temporal distributions of rainfall intensities, velocity of rain-cells, vertical profile of rain-cloud and life cycle of a rainfall event. Most of rainfall events occur in Thailand arise from Cumulus, Cumulonimbus and Nimbostratus clouds. The physical differences between these three cloud types lead to differences in rain drop size distributions and hence ground rainfall intensities of the three rainfall types. This paper aims to study physical characteristics of different rain-cloud types using weather radar data. We propose criteria to classify rainfall events that arise from Cumulus, Cumulonimbus and Nimbostratus clouds in both summer and rainy seasons. The relations between radar reflectivity and rainfall rate ($Z = aR^b$) of the three rain-cloud types were investigated and used to estimate rainfall intensities and rainfall distributions of 3-year historical rainfall data. The utility of the derived *Z-R* relationships was verified by using rainfall events that had not been used for the calibration. Fifty-four rainfall events occurred over the Northeastern part of Thailand that recorded from the Pimai radar were used in the analysis. The results obtained from this study showed that the parameters that represent horizontal characteristics of each rain-cloud type obtained from radar data can be used for classifying the type of a rainfall event correctly about 83%. The ***a*** parameters of the proposed *Z-R* relationships of Cumulus, Cumulonimbus and Nimbostratus rain-clouds were increased respectively, if ***b*** parameter was fixed. The proposed *Z-R* relationships gave more accurate radar rainfall than $Z=200R^{1.6}$ (Marshall and Palmer, 1948) and $Z=300R^{1.4}$ (the existing *Z-R*). Rainfall amount and rainfall intensity of rainfall events calculated from the proposed *Z-R* relationship of each rain-cloud type were corresponding to their physical characteristics. Based on the data used in this study, it was found that Cumulonimbus rain-clouds that occurred during rainy season produced the highest rainfall amount and raining area. Cumulus rain-clouds that occurred in summer produced the highest rainfall intensity while Cumulus rain-clouds that occurred in rainy season gave the smallest raining area. Nimbostratus rain-clouds that occurred in rainy season gave the smallest rainfall intensity and rainfall amount.

Keywords: *Weather radar, Cloud characteristics, Radar rainfall, Z-R relationship, Rainmaking*

1. INTRODUCTION

The use of data from a weather radar network is an efficient way of observing the detailed structure and behaviour of rainfall field. Weather radar provides spatially and temporally continuous measurements covering large area, that can be used almost simultaneously as the storm occurs. These characteristics make the weather radar to be an attractive instrument of rainfall measurement. While rain gauges are widely used to measure point rainfall in the field. They can provide reasonably accurate measurements at pre-selected within a catchment, but spatial integrity is lacking when these point measurements are extrapolated to provide estimates of areal distributions (Chumchean, 2004). This paper has integrated the strong points of both rain gauge and radar to evaluate rainfall that arise from different cloud types. Knowledge on rain-cloud characteristics will be useful for hydrometeorological, water resources management and agricultural. Moreover, it can help to improve an efficiency of rainmaking activities. The aims of this paper are 1) to study physical characteristics and dynamics of rainfall events that arise from different rain-cloud types; 2) to propose a classification criteria for classifying type of a rainfall event; 3) to estimate a suitable *Z-R* relationship for each rain-cloud type and 4) to evaluate rainfall intensity, rainfall amount and raining area of rainfall events that arise from different cloud types during summer and rainy seasons.

The paper is organized as follow. Section 2 describes data used in this study. Section 3 provides details of physical characteristics and dynamics of rainfall events that arise from different cloud types. Section 4 presents the proposed criteria for classifying type of a rainfall event. Section 5 analyzes the *Z-R* relationship of each rain-cloud type. Section 6 shows the results of evaluating of radar rainfall of events that arise from different types of cloud. Finally, the conclusions from this study are drawn in Section 7.

2. DATA USED IN THIS STUDY

The 2.5-km **C**onstant **A**ltitude **P**lan **P**osition **I**ndicator (CAPPI) data recorded from the Pimai radar during 2003-2005 and rain gauge data recorded from 50 automatic rain gauge stations as illustrated in Figure 1 were used in this study. The Pimai radar is a S-band radar which owned and operated by the Bureau of Royal of Rainmaking and Agricultural Aviation, Thailand. The CAPPI products have 6 minutes and 1 km^2 temporal and spatial resolutions, respectively.

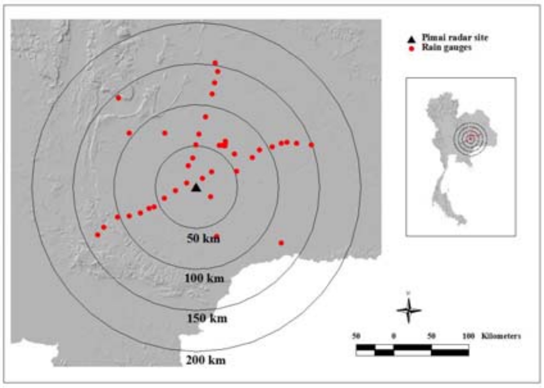


Figure 1. Map of the study area, showing rain gauges (small circles) and the Pimai radar (triangle) and 50-km range rings

The quality control of reflectivity and rain gauge data were performed. The errors due to radial anomality, ANAPROP, other signals that did not represent rainfall and errors caused by electronic problems were removed from the measured reflectivity data. Quality control of rain gauge rainfall was performed by comparing rainfall data of the considered rain gauge with rainfall data of the nearby stations. Rainfall data of the considered rain gauge should be consistent with rainfall data of the adjacent stations. Only reliable radar and rain gauge data were used in the analysis. Based on quality control of both reflectivity and rain gauge data, 54 rainfall events occurred during 2003-2005 were selected for use in the analysis. Reflectivity data that were greater than 53 dBZ were limited to 53 dBZ to mitigate contamination from hail (Fulton et al., 1998). To avoid the effect of noise in the measured radar reflectivity, the reflectivity that are less than 15 dBZ were excluded from the analysis. The 54 selected rainfall events were divided into two groups. The first group consisted of 46 events. These rainfall events were used to derive parameters that represent horizontal characteristics and dynamics of each type of rain-cloud. The rest rainfall events were considered as validated data. These rainfall events were used to test an accuracy of the proposed rain-cloud classification criteria.

3. HORIZONTAL CHARACTERISTICS AND DYNAMICS OF A RAIN-CLOUD

Horizontal characteristics and dynamics of a rain-cloud can be explained using radar CAPPI products. Radar CAPPI data provide information on spatial variability of rainfield including shape and size of rain-cells and spatial variation of rainfall intensities (which illustrated in form of reflectivity values). The horizontal characteristics of each rain-cloud are different due to differences in physical phenomenon of each rain-cloud type which can be summarised below:

- *Cumulus rain-cloud* consists of small single cells with high rainfall rate.
- *Cumulonimbus rain-cloud* consists of large raining areas around the centers of rain-cell. This rain-cloud type occurs from medium rain-cells that gather together. Rainfall intensities can be separated into two groups which are; 1) high rainfall intensities around the centers of rain-cell; 2) moderate to low rainfall intensities at the area far away from the centers of rain-cell.
- *Nimbostratus rain-cloud* consists of large raining area without centre of rain-cell that can lead to heavy rainfall. Rainfall intensity is low.

Since horizontal characteristics of each rain-cloud type are different, classifying type of a rainfall event can be preliminary performed by visual interpretation from two-dimensional CAPPI radar reflectivity. It should be noted that based on available data used in this study, there was no rainfall event that arose from Nimbostratus cloud during summer. This type of rain-cloud is hardly found in Thailand. Therefore, according to visual interpretation from the CAPPI data, the calibrated rainfall events were divided into 5 groups which included; 1) Cumulus rain-cloud during rainy season (11 events); 2) Cumulonimbus rain-cloud during rainy season (19 events); 3) Nimbostratus rain-cloud during rainy season (3 events); 4) Cumulus rain-cloud during in summer (11 events) and 5) Cumulonimbus rain-cloud during summer (2 events). Parameters that can be used to explain horizontal characteristics and dynamics of these 46 calibrated rainfall events were estimates as presented next.

3.1. Raining area of a rain-cloud

Raining area of each type of rain-cloud is different. Cumulus rain-could has the smallest raining area compared to other types of rain-cloud because it occurs from vertical convection of heats from a surface. This rain-cloud type often occurs during summer. However, in the case that the Cumulus rain-cloud composes of several large rain-cells, it can lead to large raining area. The results of this study showed that the Cumulonimbus rain-clouds had the largest raining area compared to the other two types of rain-cloud. This is because they have been influenced by moist airs which frequently occur during rainy season. On average, the raining area of Cumulonimbus, Nimbostratus and Cumulus rain-clouds were between 5,200-25,000 km^2, 3,000-6,000 km^2 and less than 5,200 km^2, respectively. The average raining area of each rainfall event of different rain-cloud types were presented in Figure 2.

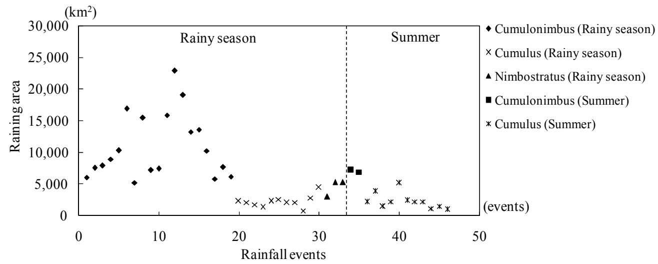


Figure 2. Raining area of each rain-cloud type

3.2. Dynamics of a rain-cloud

The important factors that have an affect on dynamics of a rain-cloud are wind velocity and its direction. Tracking of rain-cloud movement can provide information of rain-cloud velocity. In this study, the cell-centroid tracking method was used to estimate velocity of each rain-cell (Dixon and Weiner, 1993), thereafter the average velocity of a rainfall event was calculated. The results obtained from this study showed that the means velocity of Cumulus and Cumulonimbus rain-clouds were close to each other which were between 3 to 10 m/s. The mean velocity of Nimbostratus rain-cloud was quite low which was less than 3 m/s. The average velocity of rainfall events that occurred in rainy season was higher than summer. The rainy Cumulonimbus rain-clouds were in the northwest and northeast directions. The first direction is due to the influence of tropical cyclones that originated from the south China sea and Pacific

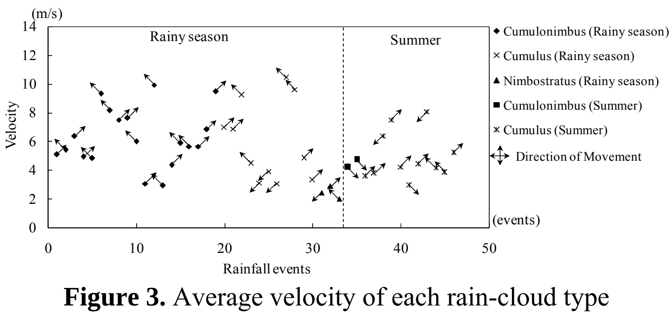


Figure 3. Average velocity of each rain-cloud type

ocean while the later direction is due to the southwest monsoons which occur during May of each year. The direction of summer Cumulonimbus rain-clouds was in the southeast because it has been influenced by an expanding of high pressure from the Gulf of Thailand (Silverman et al., 1986). Directions of movement of the Cumulus rain-clouds that occurred during summer and rainy seasons could not be obviously specified as they occurred from vertical convection of heats from a surface. The direction of Nimbostratus rain-clouds could not be justified since only small numbers of data were available for this study. The average velocity of a rainfall event of each rain-cloud type was illustrated in Figure 3.

3.3. Life cycle of a rain-cloud

Life cycle of rain-cloud is the time between development, mature and dissipation stages. The average life cycle of a rainfall event of each rain-cloud type was illustrated in Figure 4. The average life cycle of Cumulus, Cumulonimbus and Nimbostratus rain-clouds were about 64, 124 and 145 minutes, respectively which agreed with the theory (Houze, 1993). The average life cycle of a rainfall event of each rain-cloud type was illustrated in Figure 4.

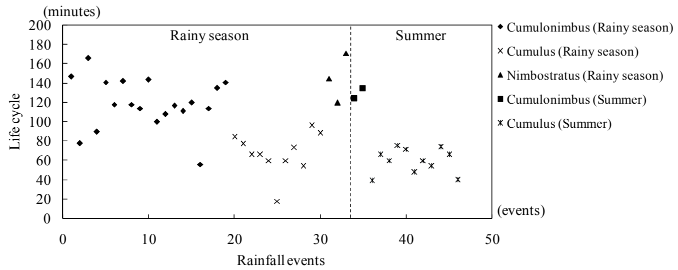


Figure 4. Life cycle of each rain-cloud type

3.4. Coefficient of spatial variation of rainfall intensity

Spatial variation of rainfall intensity of each rain-cloud type is different. This leads to a difference in coefficient of spatial variation of rainfall intensity (CV) of each rain-cloud type. The average CV of each rainfall event can be used as a parameter to identify characteristic of spatial rainfall distribution of a rainfall event. The results of this study showed that Cumulus and Nimbostratus rain-clouds had the highest and lowest average CV values, as expected which were about 0.28 and 0.17, respectively. The average CV value of Cumulonimbus rain-clouds was approximately to 0.25. The average CV of a rainfall event of each rain-cloud type was illustrated in Figure 5.

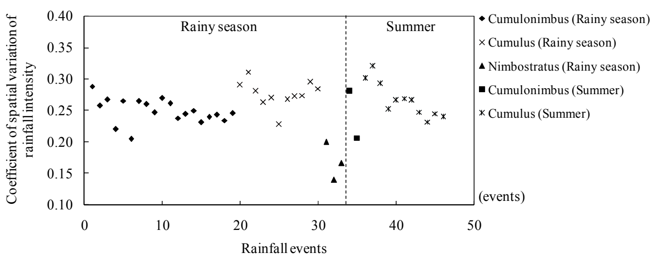


Figure 5. Coefficient of spatial variation of rainfall intensity of each rain-cloud type

3.5. Average reflectivity of a rain-cloud

Average reflectivity value of a rainfall event is corresponding to its average rainfall intensity. The result from this study showed that on average, Cumulus rain-clouds that occurred during summer had the highest average reflectivity value which was about 27 dBZ while the rainy Nimbostratus rain-clouds had the lowest average reflectivity value which was approximately to 20 dBZ. The average reflectivity values of rainy Cumulus and Cumulonimbus rain-clouds were close to each other which were about 25 dBZ. The average reflectivity value of a rainfall event of each rain-cloud type was presented in Figure 6.

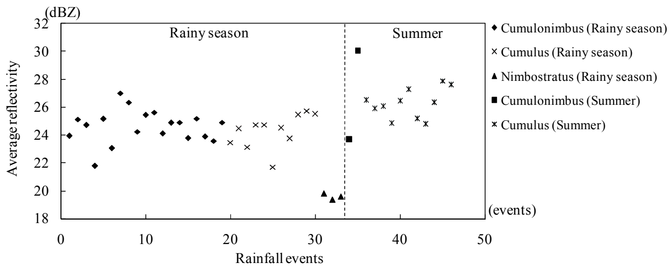


Figure 6. Average reflectivity of each rain-cloud type

4. PROPOSED CRITERIA FOR CLASSIFYING TYPE OF A RAINFALL EVENT

Forty-six rainfall events were classified into 5 groups using visual interpretation from 2-D CAPPI radar reflectivity. The horizontal characteristics and dynamics of the 5 rain-cloud types presented in the previous section were used to propose criteria for classifying type of a rainfall event based on radar CAPPI data as presented in Table 1. If all of the following 5 classification parameters of a considered rainfall event agree with the proposed classification criteria as shown in Table 1, then the type of a rainfall event can be identified, else un-classified. The proposed classification criteria were used to classify type of the validated 8 rainfall events correctly about 83%.

Table 1. Proposed classification criteria to identify type of a rainfall event for both summer and rainy seasons

No.	Rain-cloud types / Classification parameters	Cumulus 	Cumulonimbus 	Nimbostratus 
1.	Raining area : (km^2)	< 5,200	≥ 5,200	≥ 3,000
2.	Velocity : (m/s)	≥ 3	≥ 3	< 3
3.	Life cycle : (minutes)	< 100	≥ 100	≥ 120
4.	Coefficient of spatial variation of rainfall intensity	> 0.23	> 0.20	≤ 0.20
5.	Average reflectivity value (dBZ)	> 23	≥ 21	< 21

5. *Z-R* RELATIONSHIP OF EACH RAIN-CLOUD TYPE

Relationships between radar reflectivity (mm^6/m^3) and rainfall intensity (mm/h); $Z=aR^b$ of different rain-cloud types were investigated using Regression and Probability Matching Methods (PMM), (Rosenfeld et al., 1993). According to differences in the concept of these two methods, the derived *Z-R* pairs of the two methods are different. Therefore, the *Z-R* relationships obtained from these two methods were estimated separately. The ***a*** and ***b*** parameters of the *Z-R* relationship were estimated using the different series of *Z-R* pair data. These parameters were derived by minimizing Mean Square Error (MSE) between radar and corresponding rain gauge rainfall.

Doelling et al. (1998), Steiner and Smith (2000) and Hagen and Yuter (2003) studied parameters of the *Z-R* relationship using several years of Disdrometer data. They found that the most suitable ***b*** parameter was equal to 1.5. In the same way as the results from the study of Seed et al. (2002) which showed that variation of ***b*** parameter did not affect the RMSE between radar and rain gauge rainfall much. Therefore, the ***b*** parameter of 1.5 was used in this study. The ***a*** parameter of each rain-cloud type was derived by minimizing MSE between radar and corresponding rain gauge rainfall. The calibration was performed in an hourly time-step. Rainfall events of each rain-cloud type were divided into 2 groups. The first group (80% of the total rainfall events of a considered rain-cloud type) was used for calibrating the *Z-R* relationship while the second group (20% of the total rainfall events of a considered rain-cloud type) was used for validating. The *Z-R* relationships were derived using a Regression and PMM methods. Radar rainfall estimation based on the different four *Z-R* relationships [*Z-R* relationships obtained from the Regression, PMM, $Z=200R^{1.6}$ (Marshall and Palmer, 1948) and the existing *Z-R* relationship that has been used for the Pimai radar ($Z=300R^{1.4}$)] were compared with the corresponding rain gauge data in order to select the most suitable *Z-R* relationship of each rain-cloud type. Results of the *Z-R* analysis were presented in Table 2.

From Table 2, it can be seen that ***a*** parameters derived from the Regression and PMM methods varied to rain-cloud types. The ***a*** parameters of the proposed *Z-R* relationships of Cumulus, Cumulonimbus and Nimbostratus rain-clouds were increased respectively, if ***b*** parameter was fixed to 1.5. Commonly, the corresponding rainfall intensity of the same reflectivity value that arises from Cumulus rain-cloud should be higher than Cumulonimbus and Nimbostratus, respectively. This is because within a measured air volume, the Cumulus rain-cloud produces smaller number of droplets with larger size compared to the other two rain-cloud types, leading to the highest rainfall intensity. The same reasons can be said for the Cumulonimbus and Nimbostratus rain-clouds where rainfall intensity of Cumulonimbus rain-cloud is higher than Nimbostratus rain-cloud for the same reflectivity value. Moreover, it was evident that using of proposed *Z-R* relationship of each rain-cloud type gave the smallest RMSE compared to using $Z = 300R^{1.4}$ and $Z = 200R^{1.6}$ for all cases.

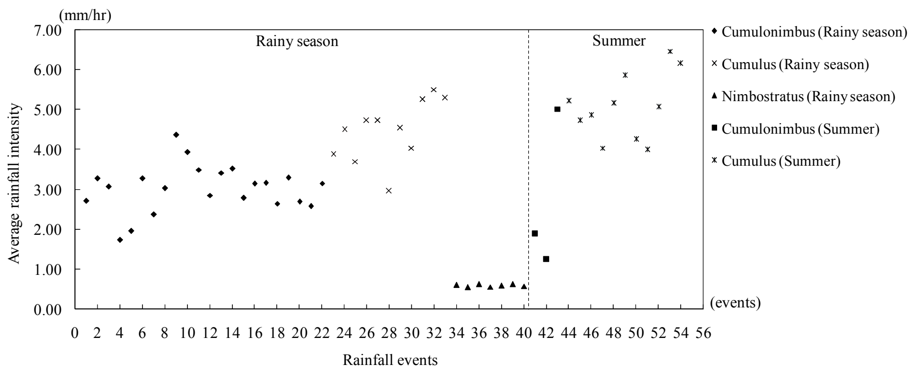
Table 2. RMSEs obtained by using difference *Z-R* relationships

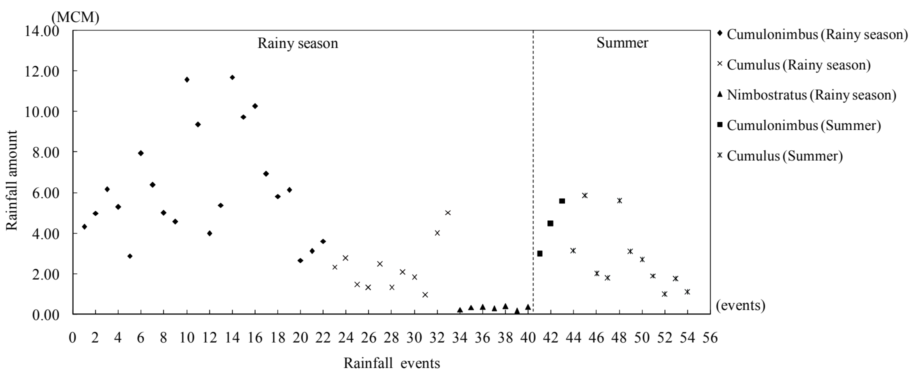
Seasons	Rain-Cloud Type	Number of Rainfall Events	RMSE (mm/hr)						Z-R pairs
			Regression $Z = aR^{1.5}$		PMM $Z = aR^{1.5}$		Marshall & Palmer (1948) ($Z = 200R^{1.6}$)	Existing *Z-R* ($Z = 300R^{1.4}$)	
			"*a*" parameter	RMSE (mm/hr)	"*a*" parameter	RMSE (mm/hr)	RMSE (mm/hr)	RMSE (mm/hr)	
Rainy	1.Cumulonimbus	Calibration (18 events)	$a = 55.19$*	6.56	$a = 38.04$	6.94	8.31	8.27	15,873
		Verification (4 events)		6.14		6.30	7.64	7.53	3,797
	2.Cumulus	Calibration (9 events)	$a = 29.06$*	7.06	$a = 23.69$	7.24	11.05	11.10	285
		Verification (2 events)		11.25		11.28	12.63	12.79	304
	3.Nimbostratus	Calibration (5 events)	$a = 283.37$	0.60	$a = 207.97$*	0.60	0.61	0.61	140
		Verification (2 events)		1.03		0.90	1.07	0.91	39
Summer	4.Cumulonimbus	Calibration (2 events)	$a = 89.71$*	8.01	$a = 41.04$	8.88	8.38	8.56	570
		Verification (1 events)		5.56		5.70	6.30	6.44	690
	5.Cumulus	Calibration (9 events)	$a = 52.09$	5.45	$a = 37.50$*	5.45	7.03	7.15	986
		Verification (2 events)		8.89		8.45	9.98	10.17	24

* *Proposed Z-R relationship*

6. EVALUATING OF RADAR RAINFALL OF THE PIMAI RADAR USING THE PROPOSED *Z-R* RELATIONSHIPS

The proposed *Z-R* relationship of each rain-cloud as presented in Table 2 were used to estimate rainfall intensity and rainfall amount of rainfall events that occurred over the study area during the study period. Rainfall intensity, rainfall amount and raining area of each rainfall event were presented in Figure 7.





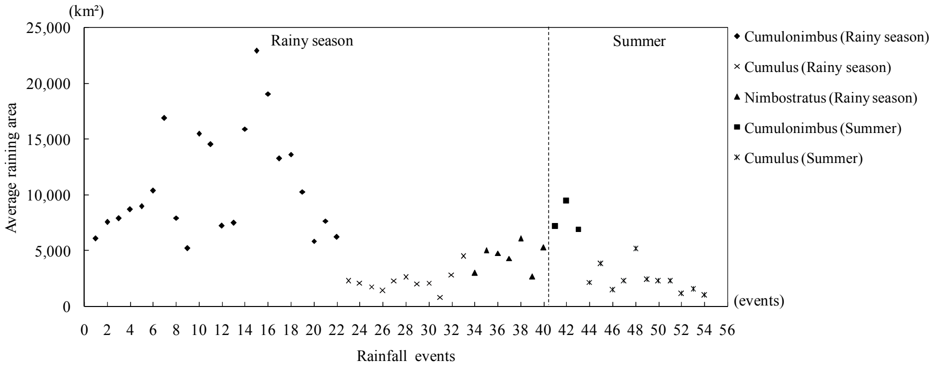


Figure 7. Evaluating of radar rainfall of events that arose from different cloud types using the proposed *Z-R* relationships.

From Figure 7, it was found that rainfall amount, rainfall intensity and raining area of rainfall events of each rain-cloud type were corresponding to their physical characteristics. Rainfall events arose from Cumulonimbus cloud during rainy seasons gave the highest rainfall amount and raining area compared to the other cloud types. Cumulus rain-clouds that occurred in summer produced the highest rainfall intensity while Cumulus rain-clouds that occurred in rainy season gave the smallest raining area. Nimbostratus rain-clouds that occurred in rainy season gave the smallest rainfall intensity and rainfall amount. This information will be useful for planning of rainmaking activities of the study area.

7. CONCLUSIONS

The conclusions from this study are as follows.

- The proposed classification criteria for classifying type of a rainfall event based on the 2.5-km radar CAPPI data can be used to identify type of a rainfall event objectively. The classification parameters consisted of raining area, average velocity, life cycle, coefficient of spatial variation of rainfall intensity and average reflectivity value of a rainfall event.
- The proposed classification criteria can identify rain-cloud type of the validated rainfall events correctly by 83%.
- The *Z-R* relationship varied to rain-cloud type. The ***a*** parameters of the proposed *Z-R* relationships of Cumulus, Cumulonimbus and Nimbostratus rain-clouds were increased respectively, if ***b*** parameter was fixed to 1.5.
- Using the proposed *Z-R* relationship of each rain-cloud type to estimate radar rainfall gave more accurate rainfall data than the ones that obtained from $Z=300R^{1.4}$ and $Z=200R^{1.6}$.
- Rainfall amount and rainfall intensity of rainfall events calculated from the proposed *Z-R* relationship of each rain-cloud type were corresponding to their physical characteristics.
- The result obtained from this study will be useful for planning and evaluating of rainmaking activities of the study area.

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