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Establishment of Z-R relationships for the Baiu precipitation using the window probability matching method

Jingyang Chen[1], Hiroshi Uyeda[2], Dong-In Lee[3] & Takeo Kinosita[4]
[1] *Frontier Observational Research System for Global Change, Japan Marine Science and Technology Center, Natsushima-cho, Yokosuka-city, Kanagawa 237-0061, Japan*
Email: chenj@jamstec.go.jp
Present affiliation: Department of Environmental Science and Engineering, Fudan University, Handan Road 220, Shanghai City 200433, P. R. China
[2] *Hydrospheric-Atmospheric Research Center, Nagoya University, Furo-Cho, Chikusa-Ku, Nagoya 464-8601, Japan*
[3] *College of Environmental and Marine Science and Technology, Pukyong National University, Pusan, Korea*
[4] *Co. SuimonKankyo, Tokyo 103-0005, Japan*

To obtain representative relationships between rain intensity and radar reflectivity and make an accurate estimation of the rainfall amount in the Baiu season (the most important rainy season in eastern Asia), the precipitation types (convective, stratiform and mixed types) must first be classified. This is because the mechanism and efficiency of precipitation show distinct variations according to rain regimes. An objective classification method, bright band fraction (BBF) that focuses on the vertical structure of radar reflectivity field, was improved and applied to the Baiu precipitation of 1995 in the Kanto Plain, Japan. Samples of convective rainfall were further divided into patterns using an index effective efficiency (Ee) that represents the echo top height. For those types (and patterns) that had been divided, Z-R relations were established using a statistical method called the window probability matching method (WPMM). The shapes of the Z-R relations show a natural matching of the probability density function of radar reflectivity with that of rain intensity recorded by rain gauge. The results show that the classification of precipitation types is reasonable, and Z-R relations corresponding to the precipitation types are representative. Some facts which need special attention in the application of the WPMM are also revealed.

1. Introduction

In eastern Asia, the precipitation process in the Baiu season which seriously affects the water and energy cycles in this area attracts much attention from meteorologists. The Baiu season usually starts in mid-June and ends at the beginning or middle of July. Because the properties of the Baiu precipitation are complicated, estimating rainfall amounts during this rainy season remains a difficult problem. At present, digital radar reflectivity data – which include information on the properties (such as the phase, size and density) of precipitation particles in the radar resolution volume – are commonly used to estimate the rainfall amount within the area covered by the radar range. Reflectivity is closely related to the rain intensity, but Z-R relationships may be quite different for various precipitation types because the mechanism and efficiency of precipitation of those types differ. For an accurate evaluation of rain intensity, Z-R relations corresponding to the types need to be established (Battan 1973). Thus, at first, the precipitation should be classified into representative types in order that one (Z) to one (R) relationship of a rainfall type can be expected. Three-dimensional radar reflectivity data obtained from volumetric scanning is often used in precipitation classification because this kind of data usually has fine temporal and spatial resolutions, and supplies abundant information about the structure of precipitating cloud and its temporal variation. Among the objective methods of precipitation classification based on three-dimensional reflectivity data, the BBF method (Rosenfeld et al. 1995), which focuses on the vertical structure of reflectivity field, is effective in classifying precipitation with complicated properties. However, to classify the Baiu precipitation objectively, the design of this method still needs to be improved to allow for the volumetric scanning mode of radar and the properties of the Baiu precipitation.

The Z-R relationship is usually shown as a power law (e.g. $Z = 200R^{1.6}$ based on Marshall & Palmer (1948)) in accordance with the theoretical relationship between reflectivity factor, rain intensity and drop size distribution (DSD). However, without detailed DSD data and accurate rainfall reflectivity information, the power law form of Z-R relationships cannot reflect the characteristics of the precipitation. Within radar scanning areas, DSD data are usually only collected at one or several spots, and cannot be used to estimate the rainfall over a large area. It has become a common practice to establish Z-R relationships by comparing the radar-observed reflectivity with the rain gauge data (e.g. Ninomiya & Akiyama 1978). Within those researches, Calheiros & Zawadzki (1987) proposed a probability matching method (PMM), which is appealing because the frequency distributions of the radar and rain gauge data are matched percentile by percentile while most methods of rain gauge adjustment only match the means of the distributions. By matching synchronous data sets of Z and R, Rosenfeld et al. (1994) proposed WPMM and overcame many of the weakness of the non-synchronous PMM. If there is a large and homogeneous sample of simultaneous radar and high-resolution recording rain gauge data, WPMM will be an elegant method (e.g. Tilford et al. 2002). However, many aspects of WPMM, such as how to apply it to actual rainfall estimation, which are its limitations, have rarely been discussed.

In this research, we objectively classified the precipitation in the Kanto area of Japan during the Baiu season of 1995 into representative types using an improved BBF method, and tried to divide samples of convective type into further detailed patterns in order to set up monotonic Z-R relations for the sub-categories within each type. With reflectivity and rain gauge data of fine temporal resolution, the WPMM is applied to establish the Z-R relations for the precipitation types and patterns. Furthermore, the representativeness of those Z-R relations in the radar scanning ranges is discussed. In this paper, a set of practical methods for accurate estimation of rainfall amount based on radar reflectivity data is provided. In addition, the points which need special attention in the application of the methods are also proposed.

2. Data

The reflectivity data is obtained from the radar situated at the top of Mt Akagi (Figure 1). The specifications of the radar are listed in Table 1. This radar scans volumetrically four times an hour (each volume scan taking 5 minutes), and a long time series of reflectivity data has been collected, which makes statistical analysis possible. The observation mode allowed 20 elevations (from -1.8° to 20°) in the volumetric scanning, which supplies detailed information in the vertical direction. The radar site is surrounded by mountainous terrain, except in the azimuthal directions of the Kanto Plain. Because of the difficulties in eliminating the effect of ground clutter, precipitation data in the Kanto Plain are chosen and analysed. To investigate the vertical temperature profile in the Kanto area, sounding data observed at the station Tateno (open circle in Figure 1) are used. The rain depth data is recorded every 10 minutes by the Japan Meteorological Agency's AMeDAS (Automated Meteorological Data Acquisition System) rain gauges.

The Baiu precipitation during the period from 19 June to 14 July 1995 in which continuous rainfall occurred in the Kanto area is chosen as our research case. Precipitation from two typhoon cases in September 1995 is also analysed to investigate the effect of applying the BBF classification method to different rainfall systems with complicated properties. Moreover, thundery rainfall in August 1995 that distinctly belongs to the convective type is divided into further detailed patterns (the method of subdividing the convective rain is described in section 3 below) for establishing corresponding Z-R relations. The analysis region is stratified into three ranges: 10∼60 km, 60∼110 km, 110∼160 km (see also Figure 1) in order to examine the range effect in the application of the WPMM. For the analysis of rain depth, we selected seven AMeDAS stations in the first range (closest range near radar), 17 stations in the second range and 15 stations in the third range, which are evenly distributed in each of the regions. Rainfall amounts recorded by rain gauges at the selected stations in the three range intervals, which are taken into the analysis, are shown in Table 2.

3. Classification of the precipitation

For type-division, reflectivity data in windows defined as 7 km (in radial direction) × 8 rays (in azimuthal direction) × 20 km (in vertical direction) and centred at the AMeDAS gauges are used. The BBF method (Rosenfeld et al. 1995) is improved and applied to the classification of the Baiu rainfall. The BBF in our work is defined as the fraction of the echo with maximum reflectivities in the 2.5 km thick air layer including the 0 °C level. The height of the 0 °C level is determined from the sounding data. In stratiform precipitation, there is often an increase in echo intensity in a narrow altitude range just below the 0 °C isotherm. The nearly horizontal band of bright echo is called the 'bright band'. The basis of the BBF method is as follows. If there are intensive reflectivities concentrated in the layer just below 0 °C level (BBF value is large), the possibility of the existence of the bright band is high, and the properties of the precipitation tend to be stratiform.

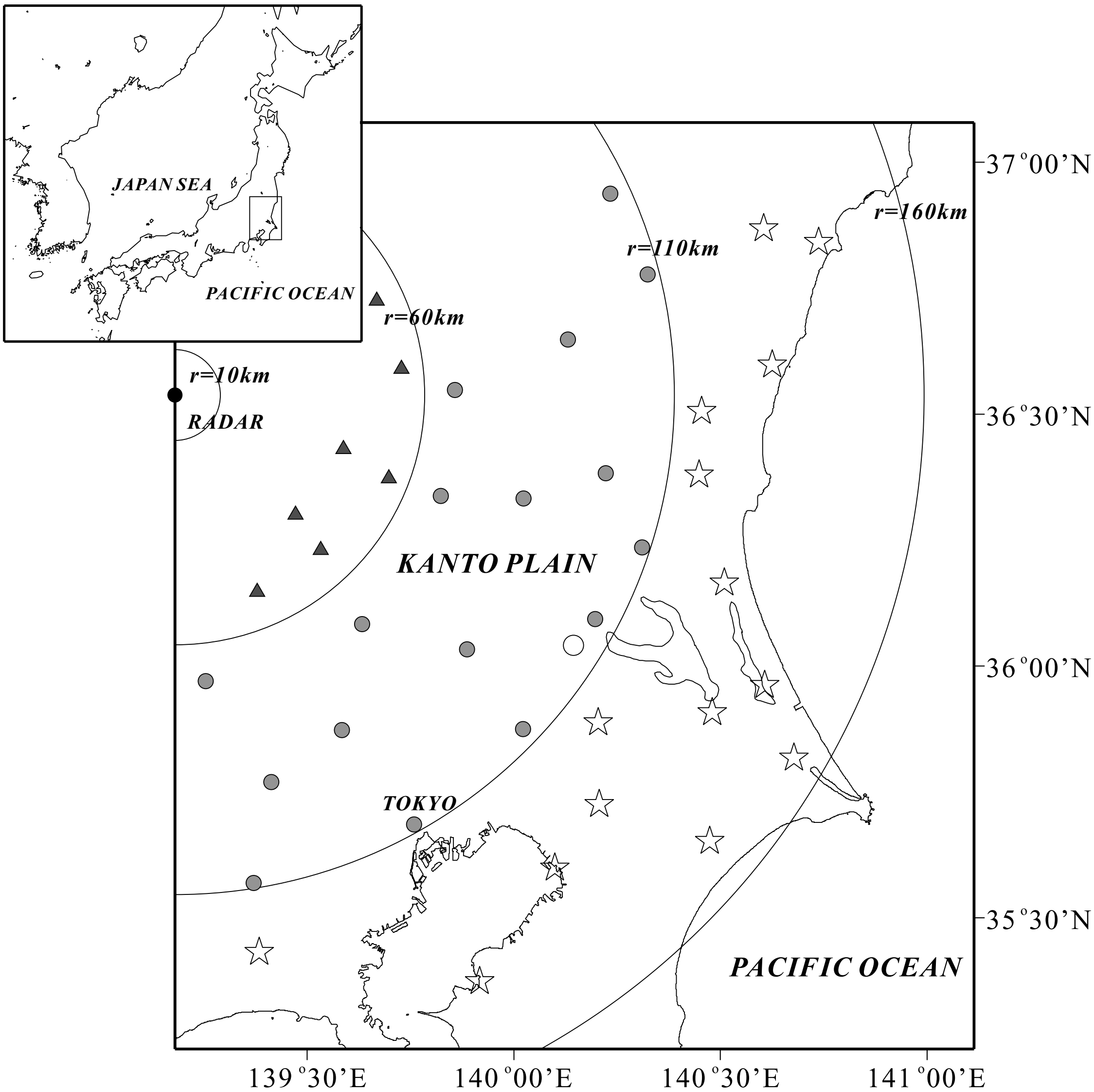

Figure 1. *Positions of radar, sounding station (open circle) and selected AMeDAS stations in three range intervals.*

On the other hand, in the convective area, where strong reflectivities are not located just near the 0 °C level but distributed along the vertical direction, the BBF value will be small. In the Baiu season, there is precipitation which has neither distinctly convective nor distinctly stratiform properties (Du 1985), which we include in 'mixed type'.

Compared to the original method, a thinner air layer (2.5 km as against 3 km) around the 0 °C level is used in our work. Because the actual bright band has a thickness of several hundred metres, using a thinner air layer can be helpful to describe the possibility of the existence of the bright band more accurately. Besides, the actual bright band exists below 0 °C level. The position of this 2.5 km thick air layer is located so that most of the layer is situated below the 0 °C level (in the original method,

Table 2. *Sum of precipitation recorded by AMeDAS rain gauges in the three range intervals (range 1: 7 gauges; range 2: 17 gauges; range 3: 15 gauges).*

Distance from radar (km)	Sum of rainfall amount (mm)		
	Baiu season	August	Typhoon
10–60	806	679	718
60–110	2183.5	861.5	1803.5
110–160	1693	588.5	2183.5

Table 1. *Specifications of the radar located at Mt. Akagi.*

Altitude of radar site (m)	Diameter of radar antenna (m)	Peak power (kW)	Wave length (cm)	Pulse duration (μs)	Beam width: Vertical Horizontal	Pulse repetition frequency (pps)	Samples in CAPPI mesh
1692	4	250	5.66 (C band)	1.98	1.04° 1.08°	450	64

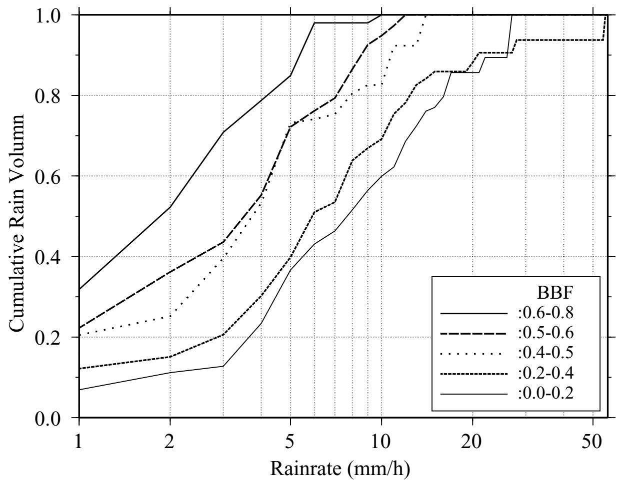

Figure 2. *Cumulative rain volume contributed by rainfall with different BBF values.*

the 0 °C level is just in the middle of that 3 km thick air layer). We could improve the original design of the BBF method because the reflectivity data we used have more detailed information in the vertical direction (there are 20 elevations in the data used in our work, while data for the original BBF method had only12 elevations).

The thresholds are chosen as $BBF < 0.4$ (convective), $BBF \geq 0.6$ (stratiform) and $0.4 \leq BBF < 0.6$ (mixed type). The fraction of the rain volume contributed to by rainfall with different BBF values to the cumulative rain volume has been calculated and is shown in Figure 2. The curve with BBF values of 0.4 ~ 0.5 is close to that with BBF 0.5 ~ 0.6, while they are distinctly different from the other curves. On the other hand, the curves with BBF values of 0.0 ~ 0.2 and 0.2 ~ 0.4 are similar to each other. These distributions indicate that three groups of rainfall samples with BBF values of 0.0 ~ 0.4, 0.4 ~ 0.6 and 0.6 ~ 1.0 have their own distinctive properties, and that the thresholds of BBF as 0.4 and 0.6 are suitable for classifying the Baiu precipitation.

The percentage of samples of the divided types is listed in Table 3. The proportion of mixed type is comparable with those of convective and stratiform types, which shows the importance of mixed type rainfall in the Baiu season. The concept of a 'transition type' has been mentioned by some researchers (e.g. Biggerstaff & Houze 1991), which suggests the area is situated between convective and stratiform regions in a typical mesoscale convective system (MCS) with trailing stratiform precipitation. Compared with the classification of Rosenfeld et al. (1995) who used $0.4 \leq BBF < 0.6$ for 'transition type' (BBF was in the original definition), it is found that the proportion of mixed type in Table 3 is much larger than that of 'transition type' in Darwin, Australia (Rosenfeld et al. 1995: table 1). This is because the 'mixed type' usually has four existing shapes (Chen et al. 2003):

Table 3. *The percentage of samples with different precipitation types in the three ranges during the Baiu season 1995.*

Distance from radar (km)	Percentage of rainfall samples of different types (%)		
	Convective	Mixed type	Stratiform
10–60	31	33	36
60–110	34	36	30
110–160	41	38	21

(1) the 'shallow convective' shape, which is with updrafts and relatively strong reflectivities in the lower layer;
(2) the 'transition' shape, which has exactly the same structure as the 'transition type' described by Rosenfeld et al. (1995);
(3) the 'edge of stratiform' shape, i.e. the edge of a spreading stratiform area; and
(4) the 'junction' shape, the junction area between convective and stratiform systems.
The existence of the 'mixed type' shows that the Baiu rainfall has complicated properties.

Based on the results of the classification, we can expect one-to-one correspondence between Z and R in a rainfall type, and the establishment of Z-R relations for the divided types becomes possible.

The improved BBF classification method seems to be widely applicable to precipitation with complicated properties. Precipitation from two typhoon cases in September 1995 was also analysed to check if the BBF method can classify typhoon precipitation suitably, and, if the Z-R relationships of those precipitation types established by the WPMM are reasonable.

The extent to which we should classify the precipitation into sub-categories in order to obtain monotonic Z-R relationships is a problem that needs to be discussed. In the convective rainfall process, properties such as the spatial distribution of the precipitating particles change significantly from one stage to another, which results in different rain intensities at different stages. We tried to divide the convective rainfall into further detailed patterns using a diagnostic parameter Ee (Rosenfeld et al. 1990). Here, Ee = (rsb-rst)/rsb, where rsb and rst are saturation mixing ratios at the bottom and the top of a precipitating cloud, respectively. The height of the bottom of a cloud was determined from sounding data while the top was derived from the radar as the average height of the grids in a window, where radar echo heights are above 2 km and reflectivities are larger that 12 dBZ. The primary lifting height larger than 300 m was chosen to avoid the effect of the turbulence near the ground. Because rst is determined by the situation at the echo top, Ee can be taken to represent the normalised height of precipitating cloud.

In August, there is usually thundery (convective type) rainfall in the Kanto area. The BBF values calculated are mostly less than 0.4. We divided the thundery rainfall into four sub-categories with different cloud heights expressed by Ee ($0.2 \le Ee < 0.4$, $0.4 \le Ee < 0.6$, $0.6 \le Ee < 0.8$ and $0.8 \le Ee < 1.0$), and established Z-R relations for those four patterns of precipitation.

4. Application of the WPMM

On the theme of precipitation assessment using radar data, the statistical methods that set up the relationship between a spatial distribution of radar reflectivity and a surface rainfall amount have been widely accepted.

Calheiros & Zawadzki (1987) proposed the PMM, based on assumptions that for a sufficiently large sample, the probability density function P(R) of rain intensity is the same in the radar scanning range. Also, the radar-measured probability of reflectivity factor P(Z) is obtained from a rain field where P(R) is identical to that recorded by the rain gauges. Thus, the Z and R are functionally related; the correct transformation from one to the other will give equal P(Z) and P(R). That is,

$$\int_{Z}^{\infty} P(Z\,|Z_0)P(Z_0)\,dZ = \int_{R}^{\infty} P(R\,|R_0)P(R_0)\,dR \qquad (1)$$

where, Z_0 and R_0 are the minimum detectable signals (MDSs) of reflectivity factor (by radar) and rain rate (by rain gauge), respectively. $P(Z|Z_0)$ is the conditional probability of Z when Z_0 has happened, while $P(R|R_0)$ has the similar meaning for R. Using (1) to match non-synchronous Z with R data sets is attractive because it allows comparison of long historical records of rain intensities with the radar reflectivities on the basis that all data belong to the same rain type.

Because equation (1) implies that the accumulated rain depth is equal everywhere within the sampling period, which is far from the real situation, it cannot be used practically. Rosenfeld et al. (1994) improved the PMM to WPMM by matching synchronous data sets of Z with R in temporal and spatial ranges (windows) that are small enough to guarantee synchronisation and collocation of the rain gauge and the radar-measured volume, but large enough to include the uncertainties. Equation (1) becomes:

$$\int_{0}^{\infty} P(Z)\,dZ = \int_{0}^{\infty} P(R)\,dR \qquad (2)$$

Integration from the zero values of P(R) and P(Z) means probabilities became unconditional, and the difficulty of determining the MDS of radar and rain gauge vanishes. The establishment of the Z-R relationship by WPMM becomes straightforward.

In our work, for the matching of Z with R, reflectivity data from 3 km (in radial direction) × 3 rays (in azimuthal direction) windows centred at the AMeDAS stations at a height of 1.5 km were used. Reflectivity data and rain gauge data of all the stations in one of the range intervals were used to match each other. By applying (2) to the divided rainfall types (patterns) within the three range intervals, Z-R relations were obtained.

5. Established Z-R relationships

5.1. Z-R relations for precipitation types classified by the improved BBF

Using the improved BBF method, precipitation for the 1995 Baiu season in the Kanto area was classified into convective, stratiform and mixed types. For the rainfall samples belonging to the divided types in the regions with different distances to the radar site, Z-R relations were set up using equation (2).

The Z-R relations of the three precipitation types differ from each other (in Figure 3, for the very large rain rates, part of the Z-R relation is not stable because of a small number of samples). The curves of convective type

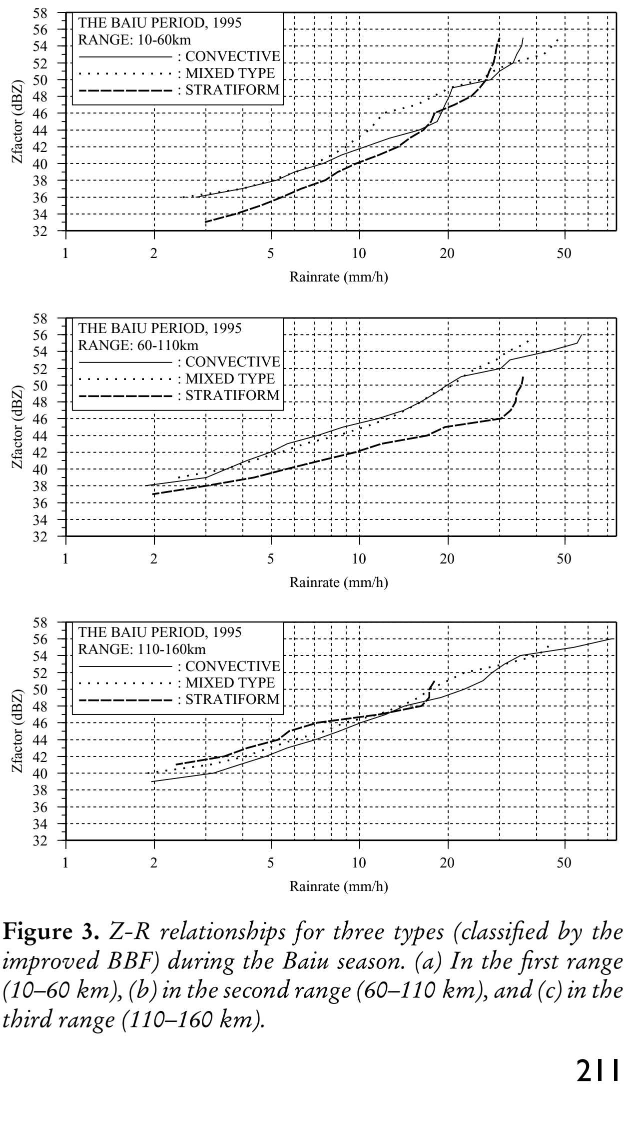

Figure 3. *Z-R relationships for three types (classified by the improved BBF) during the Baiu season. (a) In the first range (10–60 km), (b) in the second range (60–110 km), and (c) in the third range (110–160 km).*

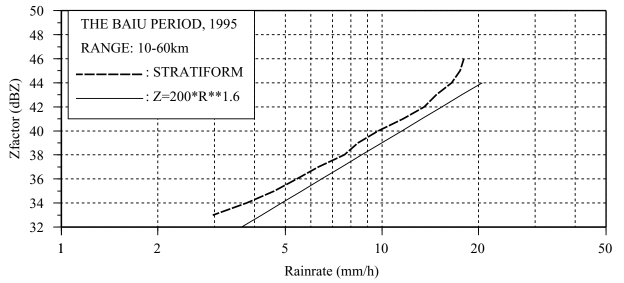

Figure 4. *Comparison of the Z-R relationship for the stratiform precipitation established by the WPMM in the first range and* $Z = 200R^{1.6}$.

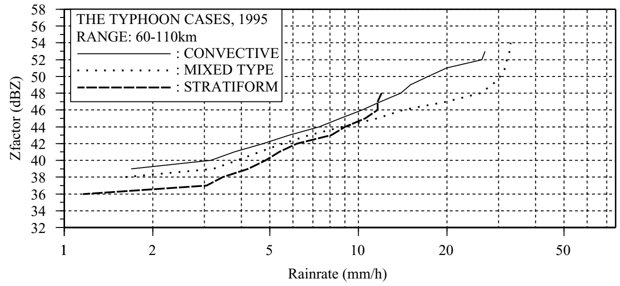

Figure 5. *Z-R relationships for typhoon precipitation of convective, stratiform and mixed types in the second range.*

deviate from those of stratiform type, which shows that there are distinct differences between the precipitation properties of these two types. The curves of mixed type are close to those of the convective type, especially in the second range. This may reflect the fact that precipitation properties of mixed type were somewhat similar to those of the convective type during the 1995 Baiu season. In Figure 3, it is also shown that the distributions of Z-R relations are different in the three ranges, the minimum detectable reflectivity (MDZ) becoming larger from the first range to the third range, due to the effect of distance from the radar site to the detected region.

For rain intensity less than 18 mm/h, the Z-R relation of the stratiform rainfall in the first range is similar to the power law Z-R relation $Z = 200R^{1.6}$ (Marshall & Palmer 1948), which is based on DSD measurement in stratiform rainfall (Figure 4). This similarity indicates that radar reflectivity can accurately express the actual reflectivity of precipitating particles in the area near the radar, and shows once again that the classification of the stratiform Baiu precipitation is reasonable. The Z-R relation of the WPMM has a little larger MDZ, and, for the same rain intensity, the corresponding reflectivity is about 1 dBZ larger than that of the M-P relation. These differences are connected to the detection capacity of the radar and the subtle difference between the stratiform rainfall in the Kanto area and that described in the M-P relation.

Within the first and the second ranges, the tendency for the same R at lower rain rates to produce larger Z in the convective area than in the stratiform area is shown in the Z-R relations (see also Figure 3). In the research of Maki et al. (2001) on tropical continental squall lines, it was found that at the same rain rate, the stratiform region has a larger maximum drop diameter and a larger median volume diameter than the convective centre and reflectivity trough regions. Though ways of comparing the rain rate are different in Maki et al. (2001) and the present work (in this paper, radar reflectivity at the height 1.5 km is used, while disdrometer data on the surface was used by Maki et al.), the difference mentioned above may reflect the fact that the features of the Baiu rainfall over the Kanto Plain and of the tropical continental squall lines are different.

It is well known that the properties of typhoon precipitation are complicated (e.g. Fujita et al. 1967). After classifying the typhoon precipitation using the improved BBF method (thresholds of BBF are the same as those used in the Baiu classification), Z-R relations were also established for the convective, mixed and stratiform types by the WPMM (see Figure 5 where Z-R relations in the second range are given as the example). The distribution of the Z-R relations of the three types are different in each of the range intervals, which express a different precipitation efficiency of the rainfall types. The shapes of the Z-R relations show a natural matching of radar reflectivity and rain intensity (except the part with very large rain intensity where the rainfall samples are small). Use of the improved BBF method is suitable for the classification of complicated rainfall – even for typhoon events. Besides, the WPMM can establish Z-R relations for the three types of the typhoon precipitation, which lays a solid foundation for the estimation of typhoon rainfall amounts based on radar reflectivity data.

Based on these Z-R relations, we used radar reflectivity to calculate the rainfall amount at the stations. The Z-R relations exactly reproduced the sum of rainfall amount in each of the three detection areas (ranges) as expected. For one precipitation type, radar reflectivity over the AMeDAS stations in a range interval and the corresponding rain intensity recorded by the AMeDAS rain gauges were taken as two sets of data for the establishment of the Z-R relationship. It is necessary for the Z-R relations to reproduce the rainfall amount correctly for the area of a range interval because those relations were actually obtained by a rain gauge adjustment method. To discuss the representativeness of the relations, the reflectivity-retrieved and gauge-recorded rain amount must be compared at every single AMeDAS station. The correlation coefficients of the retrieved and the measured Baiu rainfall amounts at the selected stations within the range intervals were calculated (Table 4). The correlation coefficients are high (at the nearest range, larger than 0.9; in the second and the third ranges, larger than 0.7). Besides these high correlation coefficients, the rainfall amount at every single gauge site could be retrieved with good accuracy. Figure 6 is an example showing the effect of the retrieval of precipitation amounts for a precipitation type in a

Table 4. *Correlation coefficient of the reproduced and recorded rainfall at the AMeDAS stations in the three ranges during the Baiu season 1995.*

Distance from radar (km)	Correlation coefficient		
	Convective	Mixed type	Stratiform
10–60	0.910	0.911	0.979
60–110	0.888	0.718	0.714
110–160	0.820	0.700	0.767

range interval, which shows that the biases of the pairs of reproduced and recorded data are small. Because the Z-R relations of the rainfall types can reproduce the rainfall amount at each of the stations, they are representative within the range intervals.

For the typhoon cases, the correlation coefficients are also high (not shown in the tables), and the biases between the reflectivity-retrieved and the gauge-recorded rain amounts at the stations are small, which shows that the classification of typhoon precipitation is reasonable, and thus the monotonic Z-R relation unique to a precipitation type in a range interval could be obtained.

The WPMM compares the radar reflectivity and the rain gauge intensity data within 'windows', whose size should be adjusted to ensure the physically connected rain intensity and radar reflectivity to match each other and encompass the timing and geometrical errors inherent in the coincident observations of radar and rain gauge. Reflectivity and rain intensity data with high temporal and spatial resolutions are required in the application of this method. Because routine rain gauge records usually have a coarse temporal resolution (e.g. about one hour), this kind of data cannot be used to calculate the P(R) that is to be matched to the P(Z). (In contrast, radar reflectivity data often satisfies this requirement in the application of the WPMM by adjusting the radar observation mode.) Data of high temporal resolution recorded by a dense rain gauge network is not commonly available; however, collecting data with a few rain gauges within the radar detecting area at frequent time intervals can be feasible. It is practicable to obtain Z-R relations by the WPMM with rain intensity data of high temporal resolution at a few rain gauges for the rainfall types reasonably classified. After the Z-R relation is verified as representative of that area, accurate estimation of rainfall amounts for the area based on radar reflectivity data can be expected.

5.2. Z-R relations for precipitation patterns divided by the Ee

Precipitation every August is mainly thundery rainfall and belongs to the convective type in the Kanto area. The corresponding BBF values calculated are mostly less than 0.4, and cannot be used to divide the thundery rainfall into further detailed patterns. Using an index Ee that can express the normalised echo top height from 0 (the lowest) to 1 (the highest), we divided the thundery rainfalls in August 1995 into four sub-categories. Z-R relations were established for those four patterns (Figure 7). In the first range, Z-R relations are similar to each other except that for $0.6 \leq Ee < 0.8$. In the second range, at lower rain rates, Z-R relations are nearly the same except for $0.8 \leq Ee < 1$. In the third range, Z-R relation of $0.6 \leq Ee < 0.8$ is very close to that of $0.8 \leq Ee < 1$ (here, the samples with $0.2 \leq Ee < 0.4$ are small thus could not give a stable Z-R relation). The groups have not got their own particular characteristics, thus the resultant Z-R relations are somewhat confused. The result of forcing the Z and R data to match each other could be seen in the first range when Ee changes between 0.8 and 1.0. Because these Z-R relations are somewhat disparate, meaningful physical rules cannot be found for the samples in the sub-categories. Hence it can be concluded that Ee does not represent the essential characteristics of the samples of different patterns in the thundery rain, and the division of stages in the thundery (convective) rainfall

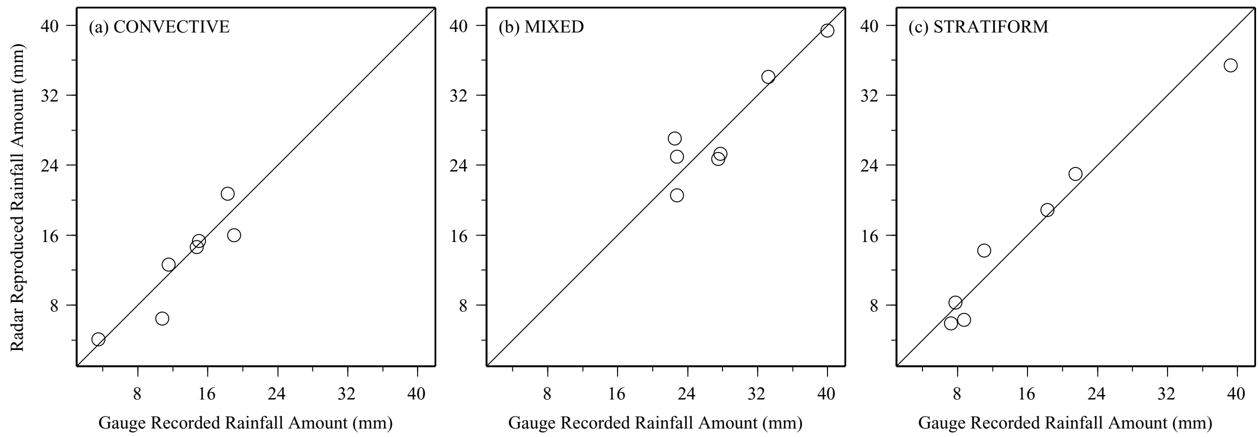

Figure 6. *Scatter diagram of the precipitation amount reproduced from radar reflecitivity and recorded by gauges in the first range during the Baiu season. (a) For convective type, (b) for mixed type, and (c) for stratiform type.*

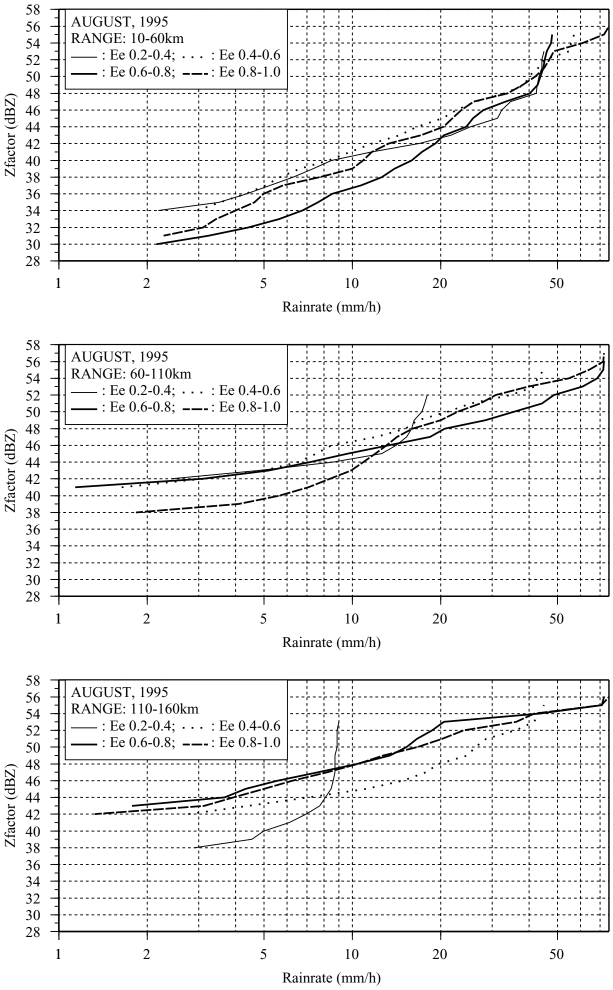

Figure 7. *Z-R relationships in August of 1995 for four patterns (divided by Ee) of convective rain. (a) In the first range, (b) in the second range, and (c) in the third range.*

by Ee is not effective. How to distinguish the patterns of the main types in order to set up corresponding Z-R relations is a problem that needs further study.

5.3. Range effect in the application of the WPMM

Because the WPMM establishes Z-R relationships using the radar reflectivity rather than the theoretical reflectivity based on drop size measurements, it incorporates the problem of measuring reflectivity of precipitating particles into its Z-R relationship. When discussing the representativeness of the Z-R relations in the radar scanning range, and understanding the physical meaning of those statistical relations (especially, for those regions far from the radar), range effect, local climatological effect and so on should all be taken into account, though it is difficult to evaluate the effects separately and quantitatively.

Correlation coefficients of the reproduced and the recorded (Baiu and typhoon) rainfall amounts at the stations in the three range intervals are shown in Figure 8. Generally, there is a tendency for correlation coefficients to decrease from the first range interval to the third range interval. This tendency indicates that the representativeness of the Z-R relations is becoming weaker as distance from the radar increases. We believe that this phenomenon is due to (1) the enlargement of the beam width along the radial moving from the radar, which lowers the radar detecting accuracy, and (2) the differences between the properties of precipitation in the area near the radar (which lies within mountainous regions) and those in the area far away from radar (which is near the sea), implying the necessity for

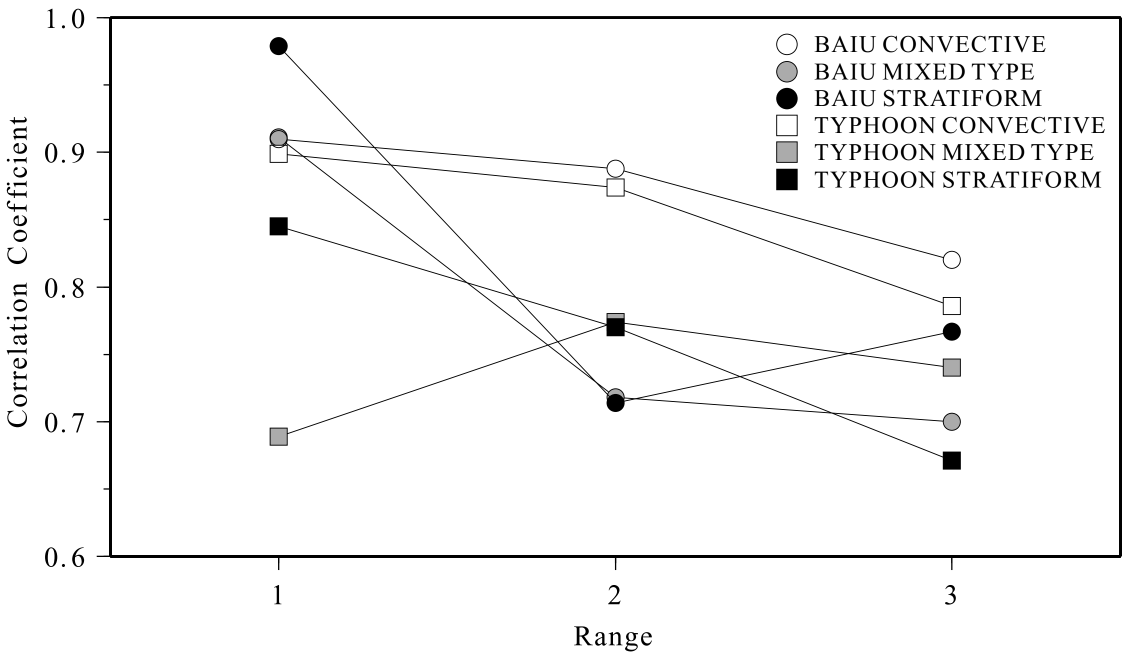

Figure 8. *Correlation coefficients of the reproduced (by reflectivity and the Z-R relations established) and recorded (by rain gauges) rainfall amounts at the stations in the three range intervals.*

further detailed specification of the characteristics of precipitation in different geographical areas. Because the detecting area of the third range interval is at a great distance (110–160 km) from the radar site, the correlation coefficients which are around 0.7 may be satisfactory but the accuracy to be expected for the rainfall amount reproduced at each of the stations is still a question that needs to be discussed.

6. Conclusions

Using radar reflectivity data, precipitation in the Kanto Plain during the 1995 Baiu season has been classified objectively. Rainfall that belongs to the convective, stratiform or mixed type is distinguished by the improved BBF method. By applying the WPMM to precipitation of the three types, representative Z-R relations are established. As expected, the Z-R relations differ from each other (the difference is especially obvious between the convective and the stratiform types), which shows the difference between the mechanism and efficiency of precipitation formation belonging to the different types. This indicates the necessity of classifying precipitation before estimating the rain amount.

Representative Z-R relations were established for the typhoon rainfall, which shows again the effectiveness of the improved BBF method in the classification of precipitation types, and presents the possibility of accurate estimation based on radar reflectivity data not only for Baiu but also for other rainfall events with complicated properties.

The correlation coefficients of the estimated and the recorded rainfall amounts at the selected stations are high, and the deviations of the estimation are small. These high correlation coefficients and low deviations show that the Z-R relations are representative in the specified regions, and imply that in an area where rain gauge data of fine temporal resolution are available at only a few stations, rainfall estimation with good accuracy can still be expected. On the other hand, those correlation coefficients become smaller in the areas at long distances from the radar, which expresses the range effect in the application of the WPMM and shows the necessity of verifying the representativeness of the Z-R relations in an area before using them to estimate precipitation amounts.

In the attempt to establish Z-R relations for rainfall samples in the sub-categories of convective type, representative relations could not be obtained, which shows the ineffectiveness of Ee in the further division of convective rainfall. The effectiveness of the estimation of rainfall amounts by radar reflectivity with WPMM-established Z-R relationships is satisfactory for the main precipitation types. However, to pursue further improvement in the accuracy of the estimation, the properties of precipitation should be studied more comprehensively in order that detailed patterns in a rainfall type can be suitably distinguished and represented.

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