Raindrop Size Distributions of Tropical Precipitation over West Sumatera

#Marzuki[1], Toshiaki Kozu[2], Toyoshi Shimomai[3]

[1]*Physics Department, Andalas University, Padang, West Sumatera, Indonesia, E-mail: marzuki@fmipa.unand.ac.id*

[2, 3] *Department of Electronic and Control System Engineering, Shimane University, Matsue, Japan*

[2]*E-mail: kozu@ecs.shimane-u.ac.jp,* [3]*E-mail: shimomai@ecs.shimane-u.ac.jp*

***Abstract*-Raindrop size distribution associated with tropical rainfall at Koto Tabang (KT) in West Sumatera of Indonesia have been measured by a two dimensional video disdrometer (2DVD) during March to May 2004. The Wadvogel N_o jump is clearly observed in some rain events at KT. However, single N_o-R relation based on N_o jump is not applicable to classify precipitation at KT. This finding may clarify the previous studies which stated that the diurnal and intraseasonal variation of DSD was clearly observed at KT. Therefore, a rain classification based on a simple threshold of rain rate is used as a preliminary method in this study. The intercept A of Z-R relation ($Z = AR^b$) found for KT precipitation in this study is smaller than those in previous studies of tropical precipitation in other climatic regions. Analysis of averaged DSD spectra for convective and stratiform rain shows that the precipitation at Koto Tabang is associated with many small drops in which stratiform DSD spectra is more concave-down than that of convective. Besides many small drops, there is also an increase in the number of large drops in convective, indicated by increasing D_o. This result is consistent with the analysis of rain rate dependent of DSDs in which two parameters of both gamma and exponential distribution (N_o, λ) decrease with increasing rain rate, indicating an increase of large drop in increasing rain rate as also shown from D_o.**

1. INTRODUCTION

Scattering and attenuation of radio waves by raindrop scatterers have attracted many researchers worldwide over the past several decades. It is well known that the attenuation and scattering of electromagnetic waves are dependent on the raindrop size distribution (DSD), therefore the DSD studies have applications in the remote measurement of rain rate, and in microwave attenuation [1]. The radio frequencies above 10 GHz suffer from attenuation due to precipitation. The need for employing higher frequencies, especially in new broadband service, has therefore encouraged research into precipitation caused attenuation.

The DSD varies both spatially and temporally not only within a specific storm type but also across differing storms types and climatic regimes [2]. It is therefore interesting to study observed data and fitted distributions from DSD collected in various locations in the world. In this study, we describe the characteristics of raindrop size distribution of tropical precipitation at Koto Tabang (0.20°S, 100.32°E), hereafter called KT. KT is located at the equator near Bukittinggi, West Sumatra in the Republic of Indonesia around 865 m above mean sea level (MSL). This region has two rainy seasons in a year (March-May and September-November), as in [3]. Here, we study the DSD of precipitation during March to May 2004.

We have organized this paper as follows: in section 2, we briefly explain the description of data used in this study and parameterization of raindrop size distribution. In section 3, we present the characteristic of Wadvogel N_o jump [4] that found in KT DSD spectra and examine whether single N_o-R relation can or not classify precipitation at KT. The gamma DSD parameters and relationship between radar reflectivity Z and rainfall rate R ($Z = AR^b$) for each distinguished rain types are also analyzed. Comparison of some functional fits to describe the KT DSD is also shown in this section. In the last section, we summarize the finding and offer concluding remarks.

2. METHODOLOGY

A. *Description of the Source Data*

The DSD observations are from a two-dimensional video disdrometer (2DVD). The components and measuring principles of the 2DVD can be found in [5]. The 2DVD can measure the size of drops with a nominal accuracy of ± 0.2 mm. Through experience, the drops smaller than 0.2 mm are measured unreliably as found in [6] and therefore, disregarded in this study. We constructed DSD for one-minute intervals, adopting a 0.1 mm channel interval from 0.25 mm to 7.45 mm. We disregarded the data in cases of rain rates of less than 0.1 mm/h as also used in [6]. Our dataset comprises a total of 4884 1-min samples and 434 mm total rainfall. A histogram of the distribution of rain rates is presented in Fig. 1. Evidently, most of the rain events had rainfall rates below 5 mm/h and only very few events had rainfall rates above 40 mm/h.

The 2DVD occasionally records spurious small drops especially in heavy rainfall. In windy condition, small drops may pass the observing area at low angles without falling into the container. These spurious drops result in false terminal fall speeds [6]. To overcome this problem, we adopted a threshold of fall speed to filter out the spurious drops using Gunn and Kinzer (GK) observation results [7], as found in previous studies [e.g., [8], [9]]. In this study, we retained the drops within ± 50% of GK observations, excluding 38% of the drops. We observed that the spurious drops vary depending upon the rain intensity in which less than 1 mm in diameter for light rain and less than 2 mm in diameter for heavy rain. We realize the shortcoming of such a filtering procedure but we used this procedure as the first step in this paper. Better procedure will be reported in the subsequent paper.

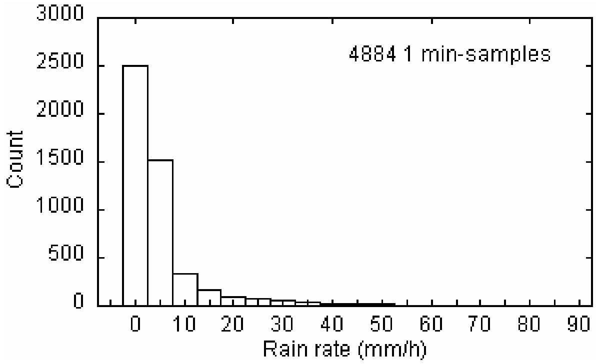

Fig. 1: Frequency distribution of rain rates at Koto Tabang .

The 2DVD and Optical Rain Gauge (ORG) were set up side by side, facilitating comparison of the rain rate observed by 2DVD with that measured by the rain gauge (Fig. 2). Considering the difference in sampling areas of the gage and 2DVD, we feel that the rain rates measured by the 2DVD are sufficiently accurate. The least square fitting of the two measurements is very close: $R_{ORG} = 1.05R_{2DVD}$ and the correlation between the two is also very high (0.99).

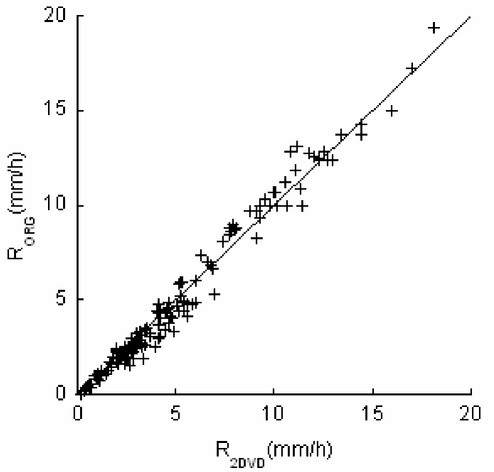

Fig. 2: A comparison of rain rates measured by ORG with those observed by 2DVD.

B. Parameterization of the Raindrop Size Distribution

The widely used gamma distribution function [2] was employed for modeling the DSD:

$$N(D) = N_0 D^{\mu} \exp(-\lambda D). \quad (1)$$

Parameters of the gamma DSD can be determined by employing the third, fourth, and sixth moments of DSD, as in [10] and using the second, fourth and sixth moments of the DSD, as in [11]. We used method in [10] in this study. The *x*th moment of DSD, M_x, is expressed as

$$M_x = N_0 \frac{\Gamma(\mu + x + 1)}{\Lambda^{\mu+x+1}}. \quad (2)$$

Using $x_1 = 3$, $x_2 = 4$ and $x_3 = 6$ as explained above, the gamma DSD parameters are obtained as follows:

$$\mu = \frac{11G - 8 + [G(G+8)]^{1/2}}{2(1-G)}, \quad (3)$$

$$G = \frac{M_4^3}{M_3^2 M_6}, \quad (4)$$

$$N_0 = \frac{\Lambda^{\mu+4} M_3}{\Gamma(\mu+4)}, \quad (5)$$

$$\Lambda = \frac{(\mu+4) M_3}{M_4}, \quad (6)$$

$$\Lambda D_0 = 3.67 + \mu . \quad (7)$$

3. RESULTS

A. Classification of Rainfall Type

Precipitation type can be identified with the help of simultaneous observations of vertical air velocities and terminal fall speeds of hydrometeors (e.g., [12], [13]). With the availability of reliable observations of rainfall DSD, it is possible to identify cloud types from rainfall received on the ground. Many studies of DSD have observed a sudden decrease in the value of the intercept parameter N_o, for exponential and gamma DSD in association with transition of rainfall type from convective and stratiform (e.g., [4], [14]). Some studies (e.g., [15], [16]) demonstrate a clear relationship between the riming process in clouds and N_o of the raindrop spectra, all of which change dramatically as riming increases, at times without a corresponding change in the rain rate. Therefore, we may logically associate small drop DSD spectra (large N_o values) with convective clouds and large drop spectra (small N_o) with stratiform mode of DSD formation since riming (an indication of updrafts and convection) is the main process determining the form of the DSD in convective clouds [17]. The author in [14] found that the relation $N_o = 4 \times 10^9 R^{-4.3}$ was a good threshold to distinguish convective and stratiform precipitation in oceanic tropical rainfall observed by Joss and Waldvogel disdrometer. Reference [18] shows the relation $N_o = 5.8 \times 10^7 R^{-4.45}$ separate cluster of points within rainfall events of tropical rain over south India into convective and stratifrom. This value is lower than those in [14].

Using 1-min spectra, jumps in N_o were also observed in this study of equatorial DSDs. Fig. 3 shows a line diagram of R vesus N_o (a) and diagram of R versus Z for rain event on 7

April 2004. It is observed from Fig. 3, that there is a clear separation of the N_o value into two groups, one corresponding to continuous, low intensity long period rainfall and the other, the high intensity, short period rainfall. Although the shift in N_o is not always unambiguous, the line N_o = 5.8 x $10^9 R^{-6.6}$, was found to separate the entire events having N_o jump into two rainfall types, identified here as convective (above) and stratiform (below; Fig. 3a). This N_o–R relationship was determined by examination of some rain events having a substantial increase and decrease in N_o without a significant change in rainfall rate. Besides classification based on Wadvogel N_o jump (hereafter method 1; M1), we examined another method as comparison (hereafter method 2; M2). In M2, if change rate of rain rate is more than 1.2 mm/h/minute, or radar reflectivity (Z) is more than a given threshold of Z, rain is classified as convective, after which the rain is assigned as stratiform. The threshold of Z is determined as a function of R as follow [32]:

$$\log_{10}(Z) = -\frac{1}{1.5}(\log_{10}(R) - \log_{10}(7)) + \log_{10}(4000) \qquad (8).$$

The *Z-R* relation (8), an empirical finding from visual inspection of time series rain rate, is good enough to distinguish convective and stratiform of rain events at Gadanki, India [32].

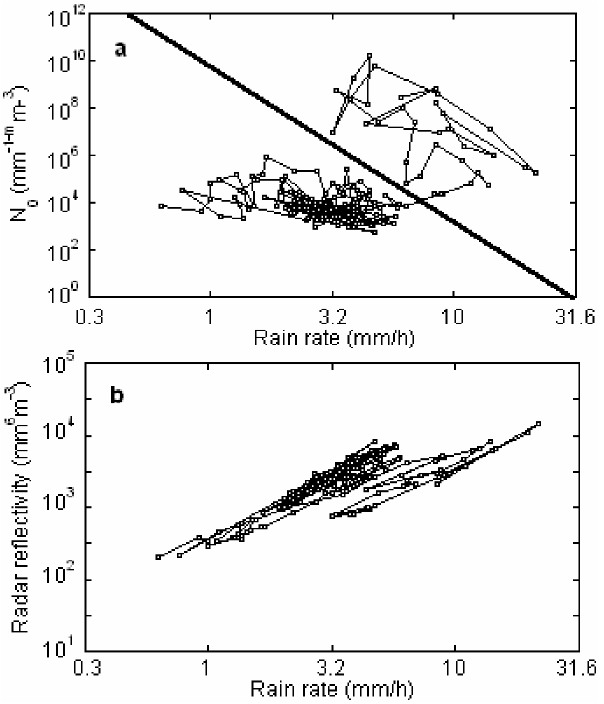

Fig. 3: A case study dated on 7 April 2004. Intercept parameter N_o of the gamma raindrop size distribution as a function of the rainfall rate. The Solid line indicates the value of N_o = 5.8 x $10^9 R^{-6.6}$ that separates the event into two contiguous groups of data points.

Table I shows the classification results using M1 and M2. For all the disdrometer data in present study, using M1, precipitation in stratiform classification was observed 55% of the time and in the convective classification 45% of time, with total rainfall was 82% convective and 18% stratiform. While classification uses M2, precipitation in stratiform type was observed 70% of the time and in the convective classification 30% of time, with total rainfall was 73% convective and 27% stratiform. The convective/stratiform ratio using M2 is in more reasonable agreement with the ratio found in the studies of tropical precipitation using Doppler radars (e.g., [34], [35]) and TRMM satellite (e.g., [36]). The author in [37] who utilized TOGA COARE data showed that intercomparison of disdrometer (based on N_o jump) and profiler measurement was in good agreement each other. However, the classification of KT precipitation based on N_o jump here contradicts previous finding based on disdrometer data (e.g., [14], [37]). KT has significant diurnal variation of DSD [38]. During March to May 2004, it was also clearly observed the intraseasonal variation of DSD at KT [39]. Because of above DSD variations, KT precipitation would not be able to be classified by using single N_o-R relation as we found in this study.

B. Z-R Relations

The traditional method of combining a set of *Z-R* points into a practicable function is to fit the points to a relation of the form $Z = AR^b$, where A and b are positive constants. In this study we calculated the *Z-R* relation for convective and stratifrom rains by using $\log_{10}(Z) = \log_{10}A + b\log_{10}R$ instead of non-linear least square of $Z = AR^b$.

Although the rain classification explained above (M1), is not good enough, we calculate the *Z-R* relations of classified spectra as comparison (Table I). Single *Z-R* relationship that applies to all the disdrometer spectra is $Z = 162R^{1.58}$ with coefficient correlation of 0.96. Empirical relation between rainfall rate and radar reflectivity in this study are $Z = 163R^{1.59}$ for stratiform and $Z = 128R^{1.6}$ for convective. Although the *Z-R* relations are dependent on the regression line and on the choice of independent variable [20], the variations in A and b also reflect the real physical difference between the types of rainfall to which the *Z-R* relations apply. Table II shows some *Z-R* relations in some references for which it is possible to clearly identify the type of rainfall.

Studies based on disdrometer data, in general suggest that, during a typical rain vents, there are the three principal types of rain (convective, transition, and stratiform), each characterized by a different *Z-R* relation. Therefore some previously reported *Z-R* relations based on didromter data included transitions rain in the convective class [29]. The author in [29] found that *Z-R* relations in [27] is contaminated by transition rains having *Z-R* relation with low coefficient of A and b such as $Z = 89R^{1.9}$ for rain event on 17 January 1993 (Table II). Besides because of the diurnal and intraseasonal variation of KT DSD, the classified rain events using N_o-R may be contaminated by transition rain, therefore the A value in convective rain is very small (Table I). The *Z-R* relation of classified spectra by (8) seems more reasonable in which convective rain has lower A value and higher b value than those of stratiform.

TABLE I: Z-R RELATIONS AND DSD PARAMETERS FOR AVERAGED DSDSPECTRA FOR CONVECTIVE AND STRATIFORM.

Methods	Rain type	No. of 1-min DSD samples	Total rainfall	Coefficient of Z-R			Gamma				Exponential	
				r	A	b	D_o	μ	λ	N_o	λ	N_o
M1	Convective	2213 (45%)	354 (82%)	0.98	80	1.80	1.62	-0.28	2.09	3225	2.22	3572
	Stratiform	2678 (55%)	81 (18%)	0.97	202	1.85	1.28	-0.18	2.72	1837	2.83	2044
M2	Convective	1470 (30%)	318 (73%)	0.95	128	1.60	1.82	0.55	2.31	4045	2.08	3454
	Stratiform	3414 (70%)	117 (27%)	0.92	163	1.59	1.1	0.64	3.90	9650	3.45	5828

Analysis of averaged DSD spectra for convective and stratiform rain shows that the precipitation at Koto Tabang is associated with many small drops in which stratiform DSD spectra is more concave-down than that of convective (see μ in Table I). The shape parameters are 0.55 and 0.64 for convective and stratiform spectra, respectively, indicating the exponential nature of the distribution. Since riming is the main process determining the form of the DSD in convective clouds, the tentative interpretation is that small rimed particle (small raindrop after melting) dominate in moderate precipitation. Besides many small drops, there is an increase in the number of large drop in convective, indicated by increasing *D*o. Updraft also gives effect to *Z-R* relations of precipitation in certain climatic region. Zenith looking radars-based on convective-stratiform algorithm developed by authors in [13] is currently being compared with the method presented here. We hope to report the result on at a later time.

TABLE II: VALUES OF A AND B IN $Z = AR^B$ FOUND IN PREVIOUS STUDIES.

Remark	A	b	Reference
Orographic	208	1.53	[21]
	109	1.64	[22]
	31	1.71	[23]
	88	1.28	[24]
Stratiform or Widespread	205	1.48	[25]
	220	1.6	[26]
	335	1.37	[27]
	367	1.3	[14]
	203	1.46	[28]
Transition	88.7	1.9	[29]
Convective	175	1.37	[27]
	139	1.43	[14]
	120	1.43	[28]

C. Variation of DSD parameters with Rain rate

Although the classification of rainfall based on N_o jump is not applicable for KT precipitation, we get more reasonable characteristics of convective-stratiform by using M2 (Table I). Startiform rain is usually dominated by light rain, while convective is dominated by moderate and heavy rain. In this section, we explore the rain rate dependent characteristics of DSDs. The instantaneous DSDs of each rainfall sample during the period observation were grouped into small classes and averaged. The rain rate dependent characteristics of averaged DSDs are studied by using gamma and exponential distribution.

Table III shows the parameter of gamma distribution. The parameter of exponential distribution is also shown as comparison. To parameterize the exponential distribution, the 3rd and 6th moments of observed spectra are used [4]. Our study demonstrate that, two parameters of both gamma and exponential distribution (N_o, λ) decrease with increasing rain rate. Our study also demonstrates that μ, as displayed in Table III, initially decreases and then increases with rain rate. We also note that the value of D_o increases with increasing rain rate, indicating a gradual broadening of the spectra. The author in [33] showed a systematic increase in intercept and a decrease in slope parameters of exponential distributions with increasing rain rate. On the other hand, the author in [14] found that all three gamma DSD parameters increase with increasing rain rate. Difference between the rain rate dependent characteristics of DSD parameters in this study from previous studies (e.g., [14], [33]), may indicate the difference in characteristics of microphysical process accompanying the formation and evolution of DSD at KT. Therefore, details analysis of microphysical process affecting DSD at KT needs to be studied in the future.

TABLE III: DSD PARAMETERS FOR DIFFERENT RAIN RATE CATEGORIES.

Rain intensity (mm/h)	Data	Gamma				Exponential	
		D_o	μ	λ	N_o	λ	N_o
$0.1 \le R < 1$	1136	0.74	1.47	6.91	80590	5.31	13596
$1 \le R < 2$	1007	0.97	0.95	4.76	19975	3.98	8240
$2 \le R < 5$	1451	1.23	0.95	3.77	11329	3.15	5858
$5 \le R < 10$	638	1.43	2.50	4.32	32426	2.86	7694
$10 \le R < 20$	354	1.71	2.49	3.60	17875	2.39	6665
$20 \le R < 40$	230	2.10	2.12	2.75	7266	1.92	4937
$R \ge 60$	68	2.36	1.21	2.07	4967	1.65	4693
All	4884	1.54	-0.39	2.13	2042	2.31	2395

D. Comparison of Three Functional Fit

Various methods can be adopted for measuring the accuracy of fit of a theoretical distribution function to an observed DSD. We used the squared error criterion as one test of accuracy of fit for some theoretical distribution functions. Squared error is defined as

$$SE = \sum_{i=1}^{75} [N_i(observed) - N_i(fit)]^2 \qquad (8)$$

where i represents the ith size category of the disdrometer. We used three years dataset to compare the three functional function fits in this study. The values quoted are averages for the entire data set for various rain rates (not from averaged DSD). The gamma function, unlike the exponential function, succeeds in reproducing the general shape of the DSD as in Table IV. The SE increases with increasing rain rate. This may be due to an increase of small and large drop at the end of spectrum. It is believed that the log normal fit has the advantage to overcome this problem. Therefore, it is worthwhile to compare the result here with that of log normal distribution in the future.

TABLE IV: AVERAGE VALUES OF SE IN $M^{-6}MM^{-2}$ FOR VARIOUS CATEGORIES OF RAIN RATE. (THE VALUES IN THE TABLE HAVE BEEN DIVIDED BY 10^7)

Rain Rate (mm/h)	Distribution Function		Number of Cases
	Exponential	Gamma	
$0.1 \le R < 1$	3.529	0.143	10919
$1 \le R < 2$	7.408	0.143	8821
$2 \le R < 5$	9.208	0.151	10596
$5 \le R < 10$	8.433	0.139	4389
$10 \le R < 20$	6.898	0.196	2316
$20 \le R < 40$	3.919	1.663	1292
All	6.814	0.392	38846

4. CONCLUSIONS AND DISCUSSIONS

The two dimensional video disdromter (2DVD) set up at Koto Tabang provided a unique opportunity to study the characteristics of DSD and its role with respect to radar rainfall measurement. Three parameters of gamma-fitted distribution are applied to each 1-min observed raindrop spectra. A relationship between intercept parameter and rainfall rate (N_o-R) is determined from dramatic decreases or increase in N_o during rainfall events with little change in rain rate. The value of N_o-R relationship, that separates the entire event having N_o jump into two rainfall types is given by 5.8 x $10^9 R^{-6.6}$, which is different from previous findings that may be due to different instrument and method in calculating the gamma DSD. However, the single N_o-R relation based on N_o jump is not applicable for KT precipitation. This finding may clarify the previous studies which stated that the diurnal and intraseasonal variation of DSD was clearly observed at KT (e.g., [38], [39]). Therefore, single N_o-R relation may not be applicable to classify all of rain events at KT.

The A value found for KT precipitation in this study is smaller than those in previous study of tropical precipitation. Analysis of averaged DSD spectra for convective and stratiform rain shows that the precipitation at Koto Tabang is associated with many small drops in which stratiform DSD spectra is more concave-down than that of convective (see μ in Table I). Besides many small drops, there is also an increase in the number of large drop in convective, indicated by increasing D_o. This result is consistent with the analysis of rain rate dependent of DSDs in which two parameters of both gamma and exponential distribution (N_o, λ) decrease with increasing rain rate, indicating an increase of large drop in increasing rain rate as also shown from D_o.

In Table II, it is shown that the orographic precipitation has the tendency of lower coefficient of A in Z-R relation. Koto Tabang is located at 865 m above mean sea level and between two mountains (Merapi and Singgalang). In the future, to clarify the finding in this study whether as reflection of KT precipitation as orographic type or not, intercomparison of DSD observed by other instruments will be conducted.

The attenuation is also a function of DSD, and A – Z relations can be therefore derived from disdrometer measurement. In the future, the relationship between rainfall derived from DSD at Koto Tabang and attenuation for a given frequency will be studied.

ACKNOWLEDGEMENT

Fruitful discussions with Prof. Daniel Rosenfeld of The Hebrew University of Jerusalem, Dr. Graham Feingold of NOAA Earth System Research Laboratory; Dr. Ali Tokay of NASA Goddard Space Flight Center, were very helpful at different stage of this research. Greatly appreciated are the help, advice and assistance of Mr. Zainul Akramin in 2DVD data processing. 2DVD observation at Koto Tabang is supported by Grant-in-Aid for Scientific Research on Priority Areas funded by the Ministry of Eduaction, Culture, Sports, Science, and Technology (MEXT) of Japan.

REFERENCES

[1] Carlos Cerro, Bernat Codina, Joan Bech, and Jeroni Lorente, “Modeling raindrop size distribution and Z(R) relations in the western Mediterranean area”, *J. Appl. Meteor.*, vol. 36, pp. 1470-1479, Nov. 1997.

[2] Carlton W. Ulbrich, “Natural variations in the analytical form of the raindrop size distribution”, *J. Climate Appl. Meteor.*, vol. 22, pp. 1764-1775, Oct. 1983.

[3] F. Renggono et al., “Precipitating clouds observed by 1.3 GHz boundary layer radars in equatorial Indonesia”, *Annales Gephysicae*, vol. 19, pp. 889-897, 2001.

[4] A. Wadvogel, “The N_o jump of raindrop spectra”, *J. Atmos. Sci.*, vol. 31, pp. 1067-1077, May 1974.

[5] M. Sconhuber, H.E. Urban, J.P.V. Poiares Baptista, W.L. Randeu, and W. Riedler, “Weather radar versus 2D-video disdrometer data. *Weather Radar Technology for Water Resources Management*, B. Braga Jr. and O. Massambani, Eds., UNESCO press, pp. 159-171.

[6] Ali Tokay, Anton Kruger and Witold F. Krajewski, “Comparison of drop size distribution measurements by impact and optical disdrometer”, *J. Appl. Meteor*. vol. 40, pp. 2083-2097, Nov. 2001.

[7] Ross Gun and G.D. Kinzer, “The terminal velocity of fall for water drops in stagnant air. *J. Meteor*., vol. 6, pp. 243-248.

[8] G. Donnadieu, “Comparison of results obtained with the VIDIAZ spectropluviometer and the Joss-Wadvogel rainfall disdrometer in a rain of a thundery type”, *J. Appl. Meteor*., vol. 19, pp. 593-597, May 1980.

[9] Daniele Hauser, Paul Amayenc, and Bernard Nutten, “A new optical instrument for simultaneous measurement of raindrop diameter and fall speed distributions, *J. Atmos. Oc. Sci*., vol. 1, pp. 256-269, September 1984.

[10] Toshiaki Kozu and Kenji Nakamura, “Rainfall parameter estimation from dual-radar measurements combining reflectivity profile and path-integrated attenuation, *J. Atmos. Oceanic. Tech*., vol. 8, pp. 259-270, April 1991.

[11] Carlton W. Ulbrich and David Atlas, “Rainfall microphysics and radar properties: analysis methods for

drop size spectra", *J. Appl. Meteor*. vol. 37, pp. 912-923, Sept. 1998.

[12] Mathias Steiner, Robert A. Houze Jr., and Sandra E. Yuter, "Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data", *J. Appl. Meteor*., vol. 34, pp.1978-2007, 1995.

[13] Christopher Williams and Warner L. Ecklund, "Classification of precipitating clouds in the tropics using 915-MHz wind profilers". *J. Atmos. Oceanic Technol*., vol. 12, pp. 996-1011, 1995

[14] Ali Tokay and D. Short, "Evidence from tropical raindrop spectra of the origin of rain from stratiform and convective clouds". *J. Appl. Meteor*., vol. 35, no. 3, pp. 355-371, March 1996.

[15] A. Huggel, W. Schmid, and A. Waldvogel, "Raindrop size distribution and the radar bright band", *J. Appl. Meteor*., vol. 35, pp. 1688-1701, Oct. 1996.

[16] R.E. Stewart, J.D. Marwitz, J.C. Pace, and R.E. Carbone, "Characteristics through the melting layer of stratiform cloud", *J. Atmos. Sci*., vol. 41, pp. 3227-3237, 1984.

[17] David Atlas and C.W. Ulbrich, "An observationally based conceptual model of warm oceanic convective rain in the tropics,", *J. Appl. Meteor*., vol. 39, pp. 2165-2181, March 1996.

[18] Soma Sen Roy, R. K. Datta, R. C. Bathia and A. K. Sharma, "Drop size distribution of tropical rain over south India", *Geofizika*, vol. 22, pp. 105-130, 2005.

[19] Sandra E. Yuter and Robert A. Houze Jr., "Measurements of raindrop size distributions over the pacific warm pool and implications for Z-R relations", *J. Appl. Meteor*., vol. 36, pp. 847-867, July 1997.

[20] Edwin Campos and Isztar Zawadzki, "Instrument uncertainties in Z-R Relations", *J. Appl. Meteor*., vol. 39,no. 7, pp. 1088-1102, July 2000.

[21] Raymond Wexler, "Rain intensities by radar", *J. Meteor*., vol. 5, pp. 171-173, August 1948.

[22] B. V. Ramana Murty and S.C Gupta, "Precipitation characteristics based on raindrop size measurements at Delhi and Khandala during southwest monsoon, *J. Sci. Ind. Res*., vol. 18A. 352-371, 1959.

[23] Duncan C. Blanchard, "Raindrop size distribution in Hawaiian rains", *J. Atmos. Sci*., vol. 10, no. 6, pp. 457-472, 1953.

[24] M. Fujiwara and T. Yanase, "Raindrop Z-R relations in different altitude", *Preprints 13th Rad. Meteor. Conf.* Amer. Meteor. Soc., Boston, 380-383.

[25] M. Fujiwara, "Raindrop size distribution from individual storm", *J. Atmos. Sci.*, vol. 22, pp. 585-591, September 1965.

[26] J. S. Marshall, and W. Mck. Palmer, "The distribution of raindrop with size", *J. Meteor*., vol. 5, pp. 165-166, August 1948.

[27] A. Tokay, D. A. Short, and B. Fisher, "Covective versus stratiform precipitation classification from surface measured drop size distribution at Darwin, Australia and Kapingamarangi atoll", *Preprints 27th Rad. Meteor. Conf.* Amer. Meteor. Soc., Boston, 690-693.

[28] C. W. Ulbrich, and David Atlas, "On the separation of tropical convective and stratiform rains", *J. Appl. Meteor*., vol. 41, pp. 188-195, 2002.

[29] David Atlas et.al., "Systematic variation of drop size and radar-rainfall relations", *J. Geophys. Res*., vol. 104, no. D6, pp. 6155-6169, March 1999.

[30] I. Imai, "Raindrop size distribution and Z-R relationships, *Proc. Eighth Weather Radar Conf.,* Boston, 211-218.

[31] G. B. Foote, A Z-R relation for mountain thunderstorms", *J. Appl. Meteor*, vol. 2, pp. 229-231, Oct. 1983.

[32] Toshiaki Kozu, private communication, May 2006.

[33] Henri Sauvageot and Jean-Pierre Lacaux, "The shape of averaged drop size distributions", *J. Atmos. Sci.*, vol. 52, pp. 1070-1083, April 1995.

[34] J. F. Gamache, and R. A. Houze, Jr. "Mesoscale air motions associated with a tropical squall line", *Mon. Wea. Rev*., vol. 110, pp. 118-135, 1982.

[35] T. Wei and R. A. Houze Jr., "The GATE squall line of 9-10 August 1974", *Adv. Atmos. Sci*., vol. 4, 85-92, 1987.

[36] C. Schumacher and Robert A. Houze Jr., "Stratiform rain in the tropics as seen by the TRMM precipitation radar", *J. Climate*, vol. 16, 1739-1756, 2003.

[37] Tokay et.al., "Tropical rainfall associated with convective and stratiform clouds: intercomparison of disdrometer and profiler measurements, *J. Appl. Meteor*., vol. 38, pp. 302-319, March 1999.

[38] T. Kozu, et al., "Seasonal and diurnal variations of raindrop size distribution in Asian Monsoon region", *J. Appl. Meteor. Soc. Japan*, vol. 84A, pp. 195-209, July 2006.

[39] T. Kozu, et al., "Intraseasonal variation of raindrop size distribution at Koto Tabang, west Sumatera, Indonesia", *Geophys. Res. Letter*, vol. 32, L07803, April 2005.