THE MAXIMUM SIZE OF RAINDROPS
– CAN IT BE A PROXY OF PRECIPITATION CLIMATOLOGY ? –

Y. Fujiyoshi[1], I. Yamamura[2], N. Nagumo[3], K. Nakagawa[4], K. Muramoto[5], and T. Shimomai[6]

[1]Inst. Low Temp. Sci., Hokkaido Univ., Sapporo, JAPAN
[2]Graduate School of Environmental Science, Hokkaido Univ., Sapporo, JAPAN
[3]Sendai District Meteorological Observatory, Japan Meteorological Agency, Sendai, JAPAN
[4]National Institute for Information and Communications Technology, Okinawa, JAPAN
[5]Graduate School of Natural Science & Technology, Kanazawa Univ., Kanazawa, JAPAN
[6] Department of Electronic and Control Systems Engineering, Shimane Univ., Shimane, JAPAN

1. INTRODUCTION

Recent high-resolution cloud-resolving models require a bin model because cloud dynamics, cloud life, and the timing and area of rainfall differ between bulk and bin models (e.g., Seifert et al., 2005). The number of large raindrops decreases dramatically and deviates from a Marshall-Palmer distribution when collision coalescence and breakup processes are included in microphysical models (Hu and Srivastava, 1995). However, Beard et al. (1986) measured raindrops with maximum dimensions of up to 8 mm in a shallow convective rainband. Hobbs and Rangno (2004) also reported super-large raindrops with maximum dimensions of at least 8.8 mm and possibly 10 mm. Beard et al. (1986) and Hobbs and Rangno (2004) used a PMS 2D-P and were not able to show full images of large raindrops. Using precipitation particle image sensors (PPIS), Takahashi et al. (1995) obtained clear images of large raindrops with maximum horizontal dimensions of 10 mm in tropical clouds.

There have been extensive reports and discussions about raindrop size distributions (RSD; e.g., Marshall and Palmer, 1948; Jameson and Kostinski, 2001). However, no statistical and systematic study has been conducted on the maximum size of raindrops. There are two possible reasons for this situation. First, because drops larger than approximately 10 mm in diameter break up spontaneously (Pruppacher and Pitter, 1971), the maximum diameter of raindrops should be limited and of little scientific interest. Second, because the number of raindrops decreases exponentially with size, it is quite difficult to conclude that the measured largest raindrop is the largest raindrop of a rainfall event under spatially and temporally limited observations.

The recent invention of automated

disdrometers allows the measurement of raindrop size distributions continuously whenever rainfall occurs. However, impact-type (Joss and Waldvogel, 1967) and one-dimensional optical disdrometers and remote sensors such as vertically pointing FMCW radar, wind profilers, and polarimetric radar cannot be used to determine the exact size and shape of individual raindrops. They provide only rough or statistical RSDs. However, with the advent of the two-dimensional video disdrometer (2DVD; Schönhuber et al., 1997), raindrop size, shape, drop axis ratio (oblateness), canting angle, and velocity can be measured (Kruger and Krajewski, 2002).

2. 2DVD MEASUREMENTS AND LARGE RAINDROPS AT SAPPORO, OKINAWA, AND SUMATRA

We examined three different climatic regimes: Sapporo (subarctic region) and Okinawa (subtropical region) in Japan, and Sumatra (tropical region) in Indonesia. The 2DVD data were collected over a 4-year period from 2003 to 2006 at Sapporo (subarctic region), over a 3-year period from 2004 to 2006 at Okinawa (subtropical region) and over a 2-year period from 2005 to 2006 at Sumatra (tropical region). We used 2DVD data from April to November at Sapporo because snow particles comprise most of the precipitation from December to March.

The largest raindrops (Fig. 1) were selected from several billion raindrops. The maximum equivolumetric sphere diameters were 7.42, 7.73, and 8.59 mm at Sapporo, Okinawa, and Sumatra respectively. Most of the raindrops had an oblate shape that was almost in equilibrium (Beard and Chuang, 1987), but some had pure vertical- and mixed-phase modes (Bringi et al., 2003).

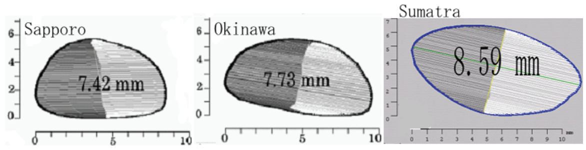

Fig. 1 Images of the largest raindrops observed at Sapporo, Okinawa, and Sumatra. The numbers indicate the equivolmetric sphere diameter.

3. APPEARANCE FREQUENCY OF THE DAILY MAXIMUM SIZE OF RAINDROPS

Because the number density of raindrops decreases exponentially with size, the detection probability decreases with increasing raindrop size. Thus, the total number of raindrops might affect the maximum size of the measured raindrops. We investigated the relationship between the maximum diameter and total number of raindrops (TNR) > 0.1 mm in diameter. Hereafter, we refer to the daily maximum diameter of raindrops as the maximum size of raindrops (MSR). The MSR increased with increasing TNR when TNR was less than approximately 5 x 10^4. In contrast, the MSR was almost independent of TNR when TNR was > 5 x 10^4. The relationship between MSR and TNR was similar at three sites of observation. We examined these large data sets to examine seasonal and diurnal variation in the MSR in the following sections only when TNR was > 5 x 10^4.

Figure 2 shows MSR appearance frequencies at Sapporo, Okinawa and Sumatra. They were well represented by a Gaussian form that peaked at approximately 3.5–4.5 mm in diameter at three sites, as reported previously (e.g., Mason, 1971). The frequency of MSR $\geq$ 5.5 mm decreased dramatically at Sapporo, but remained high at Okinawa and Sumatra. Conversely, the frequency of MSR < 3 mm decreased dramatically at Okinawa, but remained relatively high at Sapporo and Sumatra.

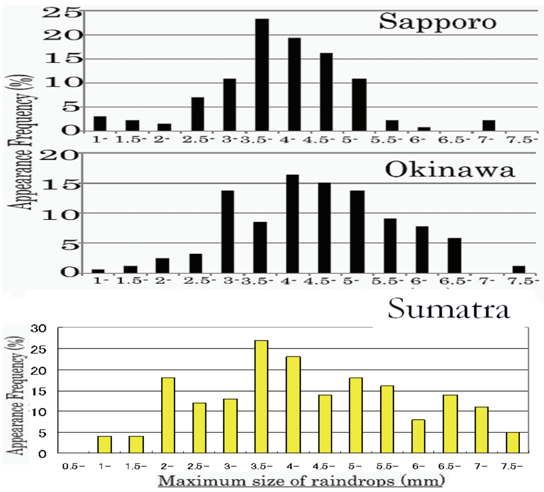

Fig. 2 Appearance frequencies (%) of the daily maximum diameter of raindrops at Sapporo, Okinawa and Sumatra.

4. SEASONAL CHNAGFES IN MAXIMUM SIZE OF RAINDROPS

The 30 largest raindrops of all raindrops measured at three sites showed a clear seasonal cycle (Fig. 3). The number of raindrops included in these 30 largest raindrops was highest in summer (June, July, and August) at Okinawa, but was highest in autumn (October) at Sapporo. This suggests that thermal (i.e., solar radiation) and dynamical (i.e., synoptic-scale disturbance) effects are the major contributors to strong convection at Okinawa and Sapporo, respectively. There are two peaks (April and September) at Sumatra, corresponding to rainy seasons.

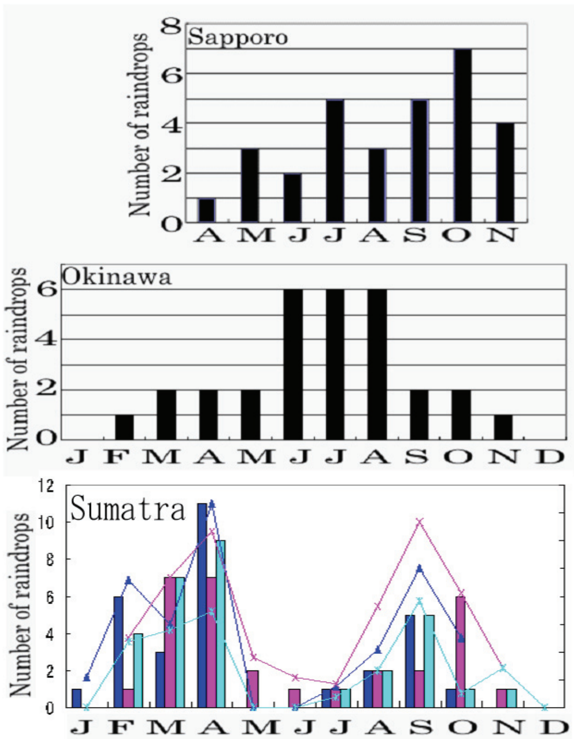

Fig. 3 Seasonal change in the number of raindrops included in the 30 largest raindrops among all raindrops measured at Sapporo, Okinawa and Sumatra.

Contrasting types of cloud create various raindrop size distributions, i.e., low-level layer clouds generate small raindrops and welldeveloped convective clouds generate large raindrops. Therefore, seasonal changes in the MSR might infer seasonal changes in the predominant types of rain cloud. We classified the MSR into three categories: small ($0.5\ mm \leq \mathrm{MSR} < 3.5\ mm$), medium ($3.5\ mm \leq \mathrm{MSR} < 5.5\ mm$), and large ($\mathrm{MSR} \geq 5.5\ mm$). The relative frequency of appearance of these three categories at Sapporo clearly changed seasonally: the appearance frequency of medium and large raindrops was highest in October, whereas that of small raindrops was highest in April. Okinawa showed seasonal changes that were distinct from those at Sapporo; the appearance frequency of medium and large raindrops was highest in August, whereas that of small raindrops was highest in winter. At Sumatra, the appearance frequency of medium and large raindrops was high in rainy seasons (April and September), whereas that of small raindrops was high in dry season.

5. DIURNAL CHANGES IN THE MSR

Diurnal changes in convective activity, precipitation, and raindrop size distributions have been reported for various climatic regimes (e.g., Fujibe, 1988; Nitta and Sekine, 1994; Dai, 2001; Kozu, et al., 2006). Peaks in these variables often occur in the late afternoon and between midnight and early morning, although the amplitude of peaks changes with climatic regime and season.

To study diurnal changes in the MSR, we checked the time at which the MSR was observed and counted the total number of occurrences in 3-h intervals (Fig. 4). The MSR tended to be higher between midnight and early morning (21–06 LST) at Sapporo (Fig. 4a), the MSR was higher in both the late afternoon (12–15 LST) and at around midnight (21–03 LST) at Okinawa (Fig. 4b), and the MSR was the highest in late afternoon (15– 18 LST) at Sumatra (Fig. 4c).

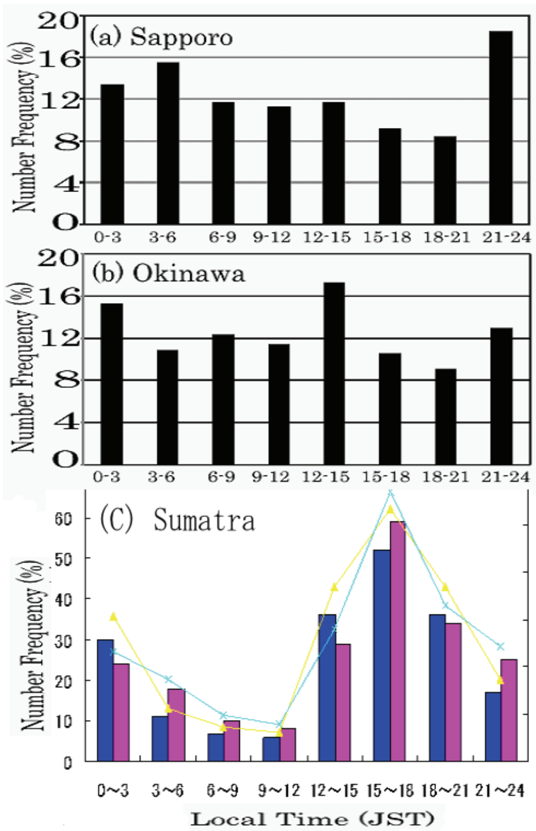

Fig. 4 Diurnal change of the occurrence frequency of the 3-h interval in which the daily maximum size of raindrops was observed at Sapporo, Okinawa, and Sumatra.

6. DISCUSSIONS

Hereafter, for convenience, we refer to raindrops with diameters between 6.5 and 7.0 mm and > 7.0 mm in equivolumetric sphere diameter as very large and super-large raindrops, respectively.

6.1 Do large raindrops fall at the very beginning of rainfall?

It is our experience that large raindrops fall at the very beginning of rainfall events, especially from shower clouds. Thus, we examined the validity of this experience. First, we selected five days on which very large raindrops were observed at Sapporo and Okinawa. Very large raindrops were not necessarily found during periods of heavy rainfall, but were often found at the beginning of rainfall events or after a pause in rainfall, as expected. Beard et al. (1986) noted that large raindrops can survive a fall of several kilometers when the concentration of small raindrops is low enough, which might explain our results.

6.2 Do large raindrops fall together?

We then checked the periods during which more than three large raindrops (≥ 6.0 mm) were found. Large raindrops fell in short periods lasting from 2 seconds at Okinawa to 149 seconds at Sapporo, when the number of large raindrops was exceptionally high from a statistical point of view. For example, the 12 largest MSRs came from raindrops that fell within 18 s (17:14:08– 17:14:26) on 10 June 2004 at Sapporo.

Beard et al. (1986) found relatively high concentrations of large raindrops within a precipitation shaft. Hobbs and Rangno (2004) surmised that super-large raindrops fall in very short-lived vertical filaments that are tens of meters across, which are known as rainshafts. Unfortunately, we made no simultaneous radar observations with 2DVD measurements. However, we succeeded in observing a rainshaft using a scanning coherent Doppler lidar (Mitsubishi Electric Co. Ltd.) at Sapporo. In vertical cross sections of S/N ratios and Doppler velocities at 14:00 JST on 23 June 2005, when a thunder cloud passed over the observation site, a strong echo 1 km in length and 200 m in width was clearly observed below the cloud base (Fig. 5). The Doppler velocity of this rainshaft exceeded 10 m s^{-1} (maximum Doppler velocity was 12.7 m s^{-1}), and time sequences of Doppler lidar images indicated that the fall velocity of this shaft was about 10 m s^{-1}. Thus, groups of large raindrops can fall from convective clouds as a narrow rainshaft. The head of the shaft forked into three branches (A, B, and C) that were somewhat similar to the high-reflectivity core that began falling approximately 10 min before each microburst (Fujita, 1992). Figures 5c and 6d indicate that Doppler velocities within branch C were larger than those within branch B, and those within branch B were larger than those within branch A. This result suggests that raindrops are sorted during their fall, even within a rainshaft, depending on their fall velocities. Interestingly, the height above ground level (AGL) of the maximum Doppler velocity (1100 m) was a few hundred meters higher than the location of the maximum value of the S/N ratio (900 m). This feature likely relates to the formation process of strong downdraft by a group of large raindrops (e.g., Feingold et al., 1991).

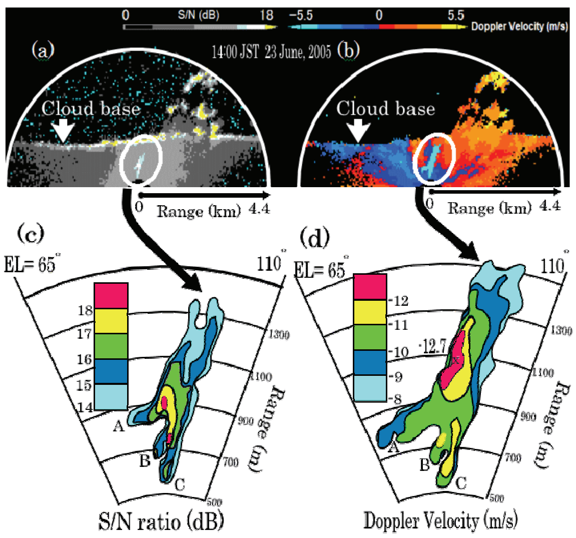

Fig. 5 Range elevation Indicator (REI) displays of (a) S/N ratios and (b) radial Doppler velocities observed by a scanning coherent Doppler lidar (Mitsubishi Electric Co. Ltd.) at 14:00 JST on 23 June 2005. Due to strong attenuation, no signals were detected above the cloud base. The lower panels show detailed structures of the (c) S/N ratios and (d) radial velocities. Negative velocity is motion downward.

6.3 How super-large raindrops are produced

It is necessary to understand how super-large raindrops are produced. Beard et al. (1986) and Hobbs and Rangno (2004) found super-large raindrops in warm, shallow convective clouds. They proposed that super-large raindrops may be produced by the rapid growth of drops that collide without breaking up, within small regions of a cloud in which the liquid water content is unusually high. At least at Sapporo, shallow, warm convective clouds were not common in October when the appearance frequency of large MSR was highest, although we cannot reject the process of collision–coalescence without break up.

Another possible process is the melting of solid hydrometeors (e.g., hailstones, graupels, and snowflakes), although the melting process of snowflakes has not yet been clarified (Fujiyoshi, 1986; Mitra et al., 1990; Fujiyoshi and Muramoto, 1996). Because large melting solid hydrometeors fall much faster than raindrops, they can survive when they fall at the very beginning of rainfall events as noted by Beard et al. (1986). They have less chance of survival when they fall during the later stages of rainfall events because of collisional break up during their fall. Using a UHF wind profiler, Kobayashi and Adachi (2001) found that raindrops > 6 mm in diameter almost disappeared during a fall from 3.25 to 3.0 km, which can be interpreted as the result of the raindrops breaking up.

We found evidence that the melting of large

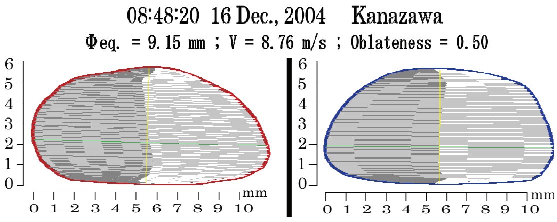

Fig. 6 The front- and side views of the largest raindrop observed at Kanazawa as well as its equivolumetric sphere diameter, vertical velocity, and oblateness.

graupels and snowflakes can produce super-large raindrops. We deployed the 2DVD disdrometer at Kanazawa, which is located in the central region of the main island of Japan facing the Sea of Japan. When the air temperature is > 0°C, melting solid hydrometeors and raindrops fall simultaneously, even in winter at Kanazawa. Super-large raindrops > 8 mm in diameter were not uncommon in winter, and the largest raindrop observed was 9.15 mm (Fig. 6).

Examples of large melting snow particles and raindrops observed on 11 and 25 January 2005 are shown in Fig. 7. On 11 January, both large melting graupels and super-large raindrops fell between 18:35 and 18:40 JST, when the surface air temperature ranged from 1 to 3°C (Fig. 7a). Most particles < 7 mm in diameter were raindrops. On 25 January, large melting snowflakes (we call the typical shape of melting snowflakes the “Mickey Mouse” shape), as well as super-large raindrops, fell between 00:24 and 00:34 JST, when the surface air temperature ranged from 7 to 8°C (Fig. 7b). Most particles < 8 mm in diameter were raindrops. The fall velocities of both melting graupels and large melting snowflakes were similar to those of super-large raindrops (approximately 8 ~ 9 m s^{-1}).

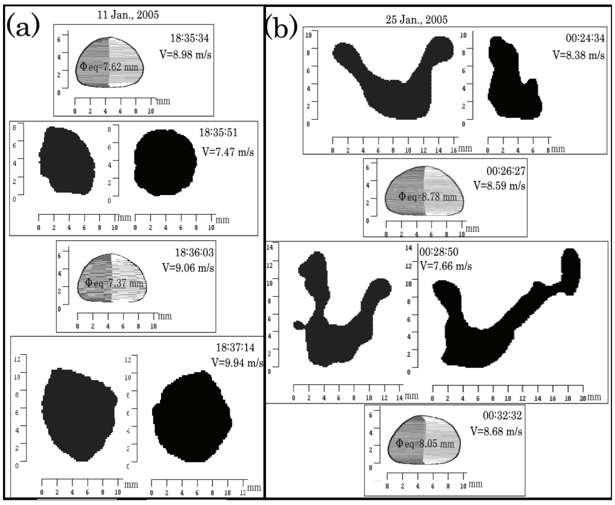

Fig. 7 2DVD images of large melting snow particles and raindrops observed on (a) 11 January 2005 and (b) 25 January 2005. The time of measurement, fall velocity, and equivolumetric sphere diameter of raindrops are also shown.

The results shown above clearly indicate that super-large raindrops can originate from melting graupels and snowflakes, which can survive a fall of several kilometers without colliding with small raindrops. The results also imply that the spontaneous break up of raindrops might limit the MSR in warm regions and seasons. Super-large raindrops > 8 mm in diameter were observed very often in winter at Kanazawa, but not at Okinawa or Sapporo. At Kanazawa, the melting level and the cloud base are usually very low in winter (< 1 km AGL). Therefore, super-large raindrops would be able to reach the ground surface before breaking up.

7. SUMMARY AND CONCLUSIONS

The maximum equivolumetric sphere diameters were 7.42, 7.73, and 8.59 mm at Sapporo, Okinawa, and Sumatra, respectively. Appearance frequencies of MSRs were well represented by a Gaussian form that peaked at approximately 3.5–4.5 mm in diameter at both regions.

MSRs > 6.0 mm occurred only in early summer (June and July) and autumn (September and October) at Sapporo, but occurred in most seasons at Okinawa. This suggests that thermal (i.e., solar radiation) and dynamical (i.e., synoptic-scale disturbance) effects are the major contributors to strong convection at Okinawa and Sapporo, respectively. At Sumatra, large raindrops fell two rainy seasons (April and September).

The MSR showed clear diurnal changes at both regions: the MSR tended to be higher between midnight and early morning (21–06 LST) at Sapporo, higher in both the late afternoon (12–15 LST) and around midnight (21–03 LST) at Okinawa, and the MSR was the highest in late afternoon (15– 18 LST) at Sumatra.

Very large raindrops (>6.5 mm) were not necessarily found during periods of heavy rainfall, but were often found at the beginning of rainfall events or after a pause in rainfall. This finding supports both our experience that large raindrops fall at the very beginning of rainfall events, and the idea that large raindrops can survive a fall when the concentration of small raindrops is low enough. Observation using a scanning coherent Doppler lidar suggests that raindrops are sorted during their fall, even within a rainshaft, depending on their fall velocities.

The 2DVD observations at Kanazawa provide evidence that the melting of large graupels and snowflakes can produce super-large raindrops. When the air temperature is > 0°C, melting solid hydrometeors and raindrops fall simultaneously, even in winter. Super-large raindrops > 8 mm in diameter were not uncommon in winter, and the largest raindrop observed was 9.15 mm.

References

Beard, K. V., D. B. Johnson, and D. Baumgardner, 1986: Aircraft observations of large raindrops in warm, shallow, convective clouds. Geophys. Res. Lett., 13, 991-994.

Beard, K. V., and C. Chuang, 1987: A new model for the equilibrium shape of raindrops. J. Atmos. Sci., 44, 1509-1524.

Bringi, V. N., V. Chandrasekar, J. Hubbert, E. Gorgucci, W. L. Randeu and M. Schöenhuber, 2003: Raindrop size distribution in different climatic regimes from disdrometer and dual-polarized radar analysis. J. Atmos. Sci., 60, 354-365.

Dai, A., 2001: Global precipitation and thunderstorm frequencies. Part II: Diurnal variations. J. Climate, 14, 1112-1128.

Feingold, G., Z. Levin, and S. Tzivion, 1991: The evolution of raindrop spectra. Part III: Downdraft generation in an axisymmetrical rainshaft model. J. Atmos. Sci., 48, 315-330.

Fujibe, F., 1988: Diurnal variations of precipitation and thunderstorm frequency in Japan in the warm season. Pap. Meteor. Geophys., 39, 79-94.

Fujita, T. T., 1992: The mystery of severe storms. WRL Research Paper 239, University of Chicago, 298 pp. [NTIS PB 92-182021]

Fujiyoshi, Y., 1986: Melting snowflakes. J. Atmos. Sci., 43, 307-311.

Fujiyoshi, Y. and K. Muramoto, 1996: The effect of breakup of melting snowflakes on the resulting size distribution of raindrops. J. Meteor. Soc. Japan, 74, 343-353.

Hobbs. P. V., and A. L. Rangno, 2004: Super-large raindrops. Geophys. Res. Lett., 31, L13102, doi:10.1029/ 2004GL020167.

Hu, Z., and R. C. Srivastava, 1995: Evolution of raindrop size distribution by coalescence, breakup, and evaporation: Theory and observations. J. Atmos. Sci., **52,** 1761–1783.

Jameson, A. R. and A. B. Kostinski, 2001: What is a raindrop size distribution? Bull. Amer. Meteor. Soc., 82, 1169-1177.

Joss, J., and A. Waldvogel, 1967: A raindrop spectrograph with automatic analysis. Pure Appl. Geophys., **68,** 240–246.

Kobayashi, T. and A. Adachi, 2001: Measurements of raindrop breakup by using UHF wind profiler. Geophys. Res. Lett., 28(21), 4071-4074.

Kozu, T., K. K. Reddy, S. Mori, M. Thurai, J. T. Ong, D. N. Rao and T. Shimomai, 2006: Seasonal and diurnal variations of raindrop size distribution in Asian Monsoon region. J. Meteor. Soc. Japan, 84A, 195-209.

Kruger, A., and W. F. Krajewski, 2002: Two-dimensional video disdrometer: A description. J. Atmos. Oceanic Technol., 19, 602-617.

Marshall, J. S. and W. M. Palmer, 1948: The distribution of raindrops with size. J. Meteor., 5, 165-66.

Mason, B. J., 1971: The Physics of Clouds, 2nd ed., 671pp, Clarendon, Oxford, U. K.

Mitra, S. K. O., V. M. Ahr and H. R. Pruppacher, 1990: A wind tunnel and theoretical study of the melting behavior of atmospheric ice particles. IV: Experiment and theory for snowflakes. J. Atmos. Sci., 47, 584-591.

Nitta, T., and S. Sekine, 1994: Diurnal variation of convective activity over the tropical western pacific. J. Meteor. Soc. Japan, 72, 627-641.

Pruppacher, H. R., and R. L. Pitter, 1971: A semi-empirical determination of the shape of cloud and rain drops. J. Atmos. Sci., 28, 86-94.

Schönhuber, M., H. E. Urban, J. P. V. P. Baptista, W. L. Randeu, and W. Riedler, 1997: Weather radar vs. 2D-video-distrometer data. Weather Radar Technology for Water Resources Management. B. Braga Jr. and O. Massambani, Eds., UNESCO Press.

Seifert, A., A. Khain, U. Blahak, and K. D. Beheng, 2005: Possible effect of collisional breakup on mixed-phase deep convection simulated by a spectral (bin) cloud model. J. Atmos. Sci., 62, .1917-1931.

Takahashi, T., K. Suzuki, M. Orita, M. Tokuno, and R. de la Mar, 1995: Videosonde observations of precipitation processes in Equatorial cloud clusters. J. Meteor. Soc. Japan, 73 (2B), 509-534.