GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L02810, doi:10.1029/2008GL036242, 2009

Diurnal to interannual variation in the raindrop size distribution over Palau in the western tropical Pacific

Tomoki Ushiyama,[1] K. Krishna Reddy,[1] Hisayuki Kubota,[1] Kazuaki Yasunaga,[1] and Ryuichi Shirooka[1]

Received 6 October 2008; revised 30 November 2008; accepted 16 December 2008; published 27 January 2009.

[1] We used a three-year dataset from an impact disdrometer to study the diurnal to interannual variation of the raindrop size distribution (DSD) over Palau in the Western Pacific warm pool. The DSD variability was primarily seasonal, with a secondary contribution due to the El Niño Southern Oscillation (ENSO) cycle. We did not find evidence of a diurnal cycle. In the seasonal cycle, mean drop diameters tended to increase during the westerly monsoon period. Within this period, drop diameters generally increased during the El Niño year and decreased during the La Niña year. However, within the easterly monsoon period, they generally increased in the winter following La Niña, and decreased in the winter following El Niño. The amplitude of the seasonal variation in mean drop diameter was approximately the same as that in Singapore and Sumatra, and about one third of that in India. **Citation:** Ushiyama, T., K. Krishna Reddy, H. Kubota, K. Yasunaga, and R. Shirooka (2009), Diurnal to interannual variation in the raindrop size distribution over Palau in the western tropical Pacific, *Geophys. Res. Lett.*, *36*, L02810, doi:10.1029/2008GL036242.

1. Introduction

[2] The raindrop size distribution (DSD) is a fundamental property of precipitation for microphysical studies and radar remote sensing. The relationship between DSD and rainfall type has been studied to calibrate radar-derived rainfall data [e.g., *Fujiwara*, 1965]. The DSD varies greatly from the mid-latitudes to the tropics [*Stout and Mueller*, 1968]. Since tropical rainfall dominates global rainfall, and the resulting heat release plays an important role in the global climate, validation of DSD in the tropics would have a great impact on climate research. Recent developments in satellite sensor technology (e.g., TRMM) require more accurate and reliable knowledge of DSD. Intensive observations using ground-based or airborne disdrometers and wind profilers have revealed rapid variation in DSD within precipitation events, which is related to convective, transition, and stratiform precipitation [*Tokay and Short*, 1996; *Yuter and Houze*, 1997; *Atlas et al.*, 1999; *Tokay et al.*, 1999]. The diurnal to seasonal variation in DSD has also been studied [*Rao et al.*, 2001; *Reddy and Kozu*, 2003; *Kozu et al.*, 2005, 2006]. *Kozu et al.* [2006] reported that the DSD in India has large seasonal variation, while that in Sumatra, Indonesia has large diurnal variation. The seasonal or diurnal variation in DSD has the same amplitude range as the variation in precipitation events.

[3] In April 2005, the Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology (IORGC/JAMSTEC) began long-term observations in the Republic of Palau, using an impact-type disdrometer. Palau is located at the center of the warm water pool in the western tropical Pacific, and has an annual rainfall of about 3500 mm. The climate in Palau is influenced by the western North Pacific monsoon (WNPM given by *Murakami and Matsumoto* [1994]). It is also affected by the ENSO cycle [*Ropelewski and Halpert*, 1987]. Therefore, Palau is a suitable location for studying long-term DSD variation in oceanic rainfall. Until March 2008, three-year disdrometer data were obtained with a tipping-bucket raingauge. We studied the diurnal to interannual variation in DSD in the western Pacific warm pool.

2. Data and Analysis Method

[4] We used disdrometer data (RD-80, Disdromet) to determine the DSD. A tipping-bucket raingauge was also used to detect the amount of rainfall. The instruments were installed near the north tip of Peleliu Island in the Republic of Palau (7°2′29″N, 134°16′7″E), which is in the warm water pool in the western Pacific. Peleliu Island has a maximum length of 10 km and a width of 3 km. It is too small to produce afternoon showers through island-surface radiative heating [*Gray and Jacobson*, 1977]. Therefore, the observations contain only a small island effect, and closely represent the oceanic DSD characteristics. The disdrometer and raingauge data were available from 24 March 2005 and 19 December 2004, respectively, until March 2008. Disdrometer data were lost twice: once from July 18 to August 2 2005 and once from January 8 to 16 2007. The data were recorded once every minute.

[5] Wind speed and relative humidity were obtained from radiosondes, which were launched twice a day from Koror in Palau (about 40 km northeast of the disdrometer observation point). To represent typical winds, the zonal and meridional wind at 850 hPa was used. The relative humidity at 700 hPa was used to calculate whether the conditions were dry or wet for effective convective development.

[6] To discuss the DSD characteristics, we used the parameter ΔZ_{MP}, which *Kozu et al.* [2005] defined as $\Delta Z_{MP} = 10\log_{10}Z - 10\log_{10}(200R^{1.6})$, where Z is a radar reflectivity factor ($mm^6\ m^{-3}$), and R is the rainfall rate (mm/h). It is expected to have similar characteristics to the median drop diameter or mass-weighted mean diameter, with a correction due to the dependence on the rainfall rate.

[1]Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan.

0094-8276/09/2008GL036242$05.00

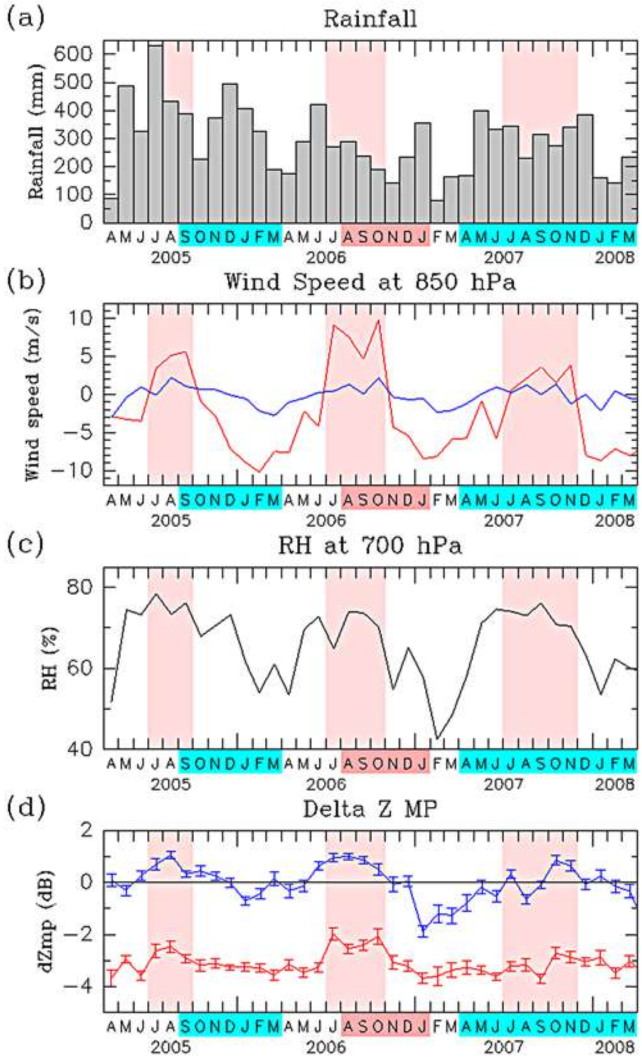

Figure 1. Time-series of (a) rainfall measured using the raingauge, (b) zonal wind speed (red) and meridional wind speed (blue), (c) relative humidity at 700 hPa, and (d) ΔZ_{MP} for light (1–3 mm/h; blue) and heavy (10–30 mm/h; red) rainfall. The error bars in Figure 1d are 95% confidence interval. The pink shading inside the panels indicates the westerly monsoon periods. The light blue and pink bars on the horizontal axis are La Niña and El Niño phases, respectively. The definitions of La Niña and El Niño phases are given in the El Niño observation reports produced by the Japan Meteorological Agency.

Data with a rainfall rate of less than 0.1 mm/h were excluded from the analysis.

3. Results

[7] As mentioned in the introduction, the climate in Palau is influenced by the Western North Pacific monsoon (WNPM). Figure 1 shows the dominant seasonal wind cycle in Palau (Figure 1b) and the relative humidity in the lower troposphere (Figure 1c), which increased in westerly periods. The onset of westerly periods occurred between June and July, and the withdrawal occurred between September and December [*Kubota et al.*, 2005]. Rainfall (Figure 1a) tended to increase during westerly periods, although rainfall was also influenced by the ENSO cycle. The local rainfall has been found to decrease in winters following El Niño, and increase in winters following La Niña [*Ropelewski and Halpert*, 1987]. The rainfall variation in Figure 1a is consistent with this pattern; rainfall increased in December 2005 and December 2007 (winters following La Niña), and decreased in February 2007 (winter following El Niño). During El Niño, the average convection center shifted to the east of Palau [*Nitta and Motoki*, 1987], which could be why the westerly wind increased in the summer of 2006.

[8] Figure 1d shows the influence of the monsoon cycle on ΔZ_{MP}. Under both heavy (10–30 mm/h) and light (1–3 mm/h) rainfall conditions, ΔZ_{MP} increased during westerly periods. The increases in drop size appear to be synchronized with lower tropospheric westerly winds and relative humidity.

[9] *Kozu et al.* [2006] studied the DSD seasonal cycle in south and southeast Asia. They found that the ΔZ_{MP} in east India (Gadanki) had the largest seasonal variation, with amplitudes of approximately 7 and 4 dBZ in 1–3 and 10–30 mm/h of rainfall, respectively. They also observed a seasonal variation of about 2 dBZ in Singapore and Sumatra for both 1–3 and 10–30 mm/h of rainfall. The amplitudes of the seasonal variation in ΔZ_{MP} in this study were approximately 2 dBZ and 1.5 dBZ, respectively, or approximately one third of that in India, and the same as that in Singapore and Sumatra.

[10] Figure 2 shows the seasonal and interannual variation in the rainfall histograms. In Figure 2, the westerly and easterly periods are represented by the months JAS and JFM, respectively. Figure 2 shows distinct seasonal differences. For small ΔZ_{MP} values (−6 to −2 dBZ), the rainfall during the westerly period (three solid lines) contributed less, while for large ΔZ_{MP} values (approximately 0 dBZ),

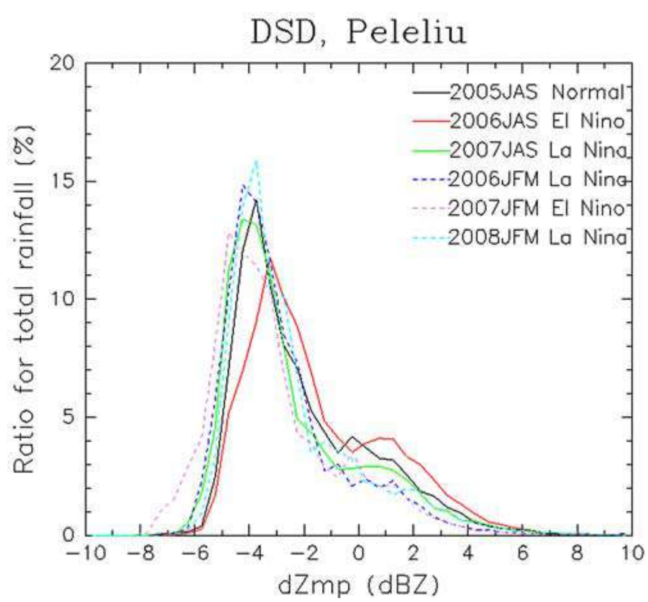

Figure 2. Histogram of total rainfall ratios as function of ΔZ_{MP}. Each line indicates the three-month average in the westerly (solid lines) and easterly (broken lines) periods of each year.

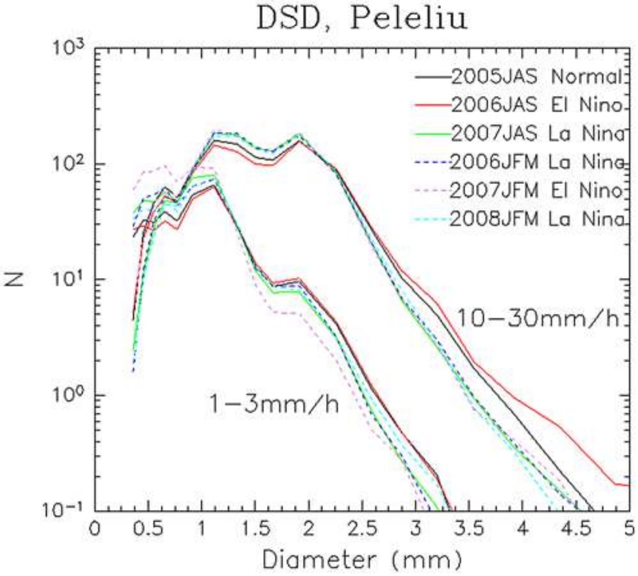

Figure 3. Drop-size distribution in the three-month average of each monsoon period and in each year. The six lines with smaller *N* (left-hand side) indicate light rainfall (1–3 mm/h), while the six lines with larger *N* indicate heavy rainfall (10–30 mm/h). The horizontal and vertical axes are droplet diameter (mm) and number of droplets, respectively. Each color indicates the same periods as in Figure 2.

the rainfall during the westerly period contributed more. As a result, the average ΔZ_{MP} increased during the westerly period.

[11] During the westerly period (solid lines), the rainfall had larger ΔZ_{MP} values in 2006 than in 2007. As a result, JAS 2006 (El Niño) had the largest ΔZ_{MP} and JAS 2007 (La Niña) had the smallest ΔZ_{MP} during the westerly period. Conversely, during the easterly period (broken lines), JFM 2007 (the winter following El Niño) had the smallest ΔZ_{MP} rainfall, making its ΔZ_{MP} smaller than in the two other years (the winters following La Niña).

[12] Figure 3 shows the DSD variation for light (1–3 mm/h) and heavy (10–30 mm/h) rainfall, to describe the interannual variation more precisely. In the westerly period (solid lines), the DSD under both heavy and light rainfall conditions showed systematic interannual variation. The DSD during the El Niño year (JAS 2006) was broader than that during the La Niña year (JAS 2007), with the normal year (JAS 2005) taking intermediate values. This is consistent with the result that the El Niño year had the largest ΔZ_{MP} during the westerly period (Figure 2).

[13] Conversely, during the easterly period (broken lines), DSD showed little interannual variation under heavy rainfall conditions. Under light rainfall conditions, however, the DSDs from the winters following La Niña (JFM 2006 and 2008) were broader, and those from the winter following El Niño were narrower. This relationship is the opposite of that found during the westerly period. The rainfall amounts in the following winters were influenced by the effect of ENSO [*Ropelewski and Halpert*, 1987]. Under dry conditions, the convective system is less organized. Consequently, the DSD tends to be narrower in the winter following El Niño. By contrast, during the westerly period, the rainfall amount is not influenced by ENSO, and consequently the DSD has different characteristics.

[14] Figure 4 compares the scatter-diagram characteristics from the El Niño and La Niña years during the westerly period. Both Figures 4a and 4b show two concentrations of observed rainfall events. One concentration is approximately in the center (about 3 mm/h and 1 dBZ) and the other is in the lower half of the panels (10–50 mm/h and −3 dBZ). The first concentration most likely corresponds to stratiform rainfall, while the second corresponds to convective or transition rainfall, analogous to previous studies [*Tokay and Short*, 1996; *Atlas et al.*, 1999]. Since separation of convective and stratiform rainfall based solely on DSD data is not accurate [*Yuter and Houze*, 1997], we will not discuss the separation into these two regions here. In general, the difference in ΔZ_{MP} between those two concentrations was approximately 4–6 dBZ, or approximately three times the seasonal variation in amplitude (Figure 1d). This suggests that the seasonal variation in DSD was not negligibly small compared to that caused by variation in rainfall type.

[15] In Figure 4a, the first concentration around the center is denser than that in Figure 4b. This suggests that during the westerly period, there was more stratiform rainfall in the El Niño year than in the La Niña year, which corresponds to

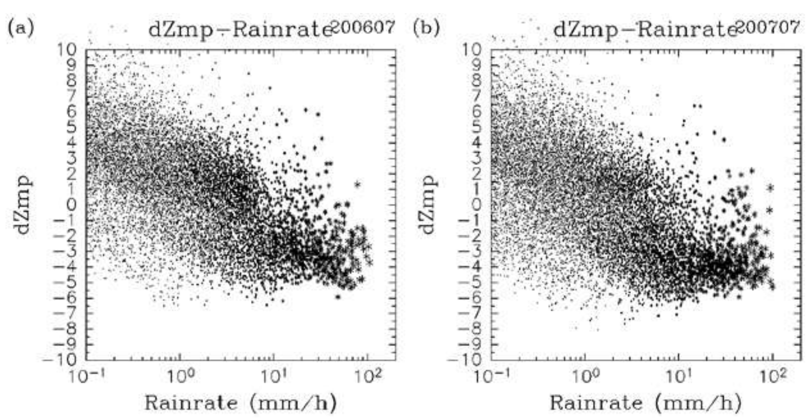

Figure 4. Scatter distribution of ΔZ_{MP} as function of the rainfall rate for (a) the El Niño year during the westerly period (JAS 2006) and (b) the La Niña year during the westerly period (JAS 2007). The diameter of each asterisk is proportional to the square root of the amount of rainfall in one minute.

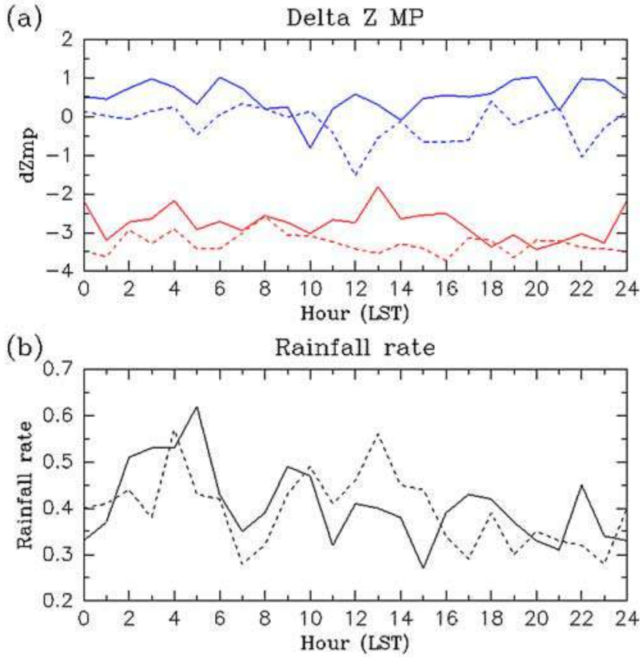

Figure 5. Diurnal variability of (a) ΔZ_{MP} for light (1–3 mm/h; blue) and heavy (10–30 mm/h; red) rainfall and (b) the rainfall rate. The solid and broken lines show the amount of rainfall during the westerly and easterly periods, respectively.

the result that El Niño year had larger ΔZ_{MP} (Figure 2) and broader DSD (Figure 3) values. In Figure 4b, the second concentration center in the lower half has much a smaller ΔZ_{MP} than that in Figure 4a. This suggests that the majority of convective or transition rainfall in the La Niña year had a smaller ΔZ_{MP} than that in the El Niño year, during the westerly period. There were extremely heavy rainfall events (over 30 mm/h) with large ΔZ_{MP} in both years, which may have originated in the convective core. However, there were so few of them that they barely affected the average DSD.

[16] Figure 5 shows the diurnal variability in ΔZ_{MP} and the rainfall rate. No significant diurnal cycle was found in ΔZ_{MP} for either light or heavy rainfall in any season, although the rainfall rate had a significant diurnal cycle, with a pre-dawn maximum (westerly period) or pre-dawn and afternoon maximum (easterly period). The observed diurnal variation in rainfall is typical for the tropical oceanic region [e.g., *Sui et al.*, 1997]. However, such variation is unlikely to be an essential factor affecting DSD.

4. Summary and Discussion

[17] We used three-year-period impact-type disdrometer data to study the diurnal to interannual variability of the DSD over Palau. The rainfall in this region is influenced by the monsoon cycle, the western north Pacific summer monsoon (WNPM), the ENSO, and the diurnal cycle. Our observations showed that the DSD was influenced primarily by the monsoon cycle, with a secondary influence from the ENSO cycle, but little influence from the diurnal cycle. The amplitude of the DSD seasonal cycle was approximately one third of that due to the differences in rainfall types. The mean diameters increased during the westerly period, and decreased during the easterly period. The amplitude of the seasonal variation in DSD was in the same range as that in Singapore and Sumatra, and approximately one third of that in India.

[18] The behavior of the interannual variation in DSD was opposite in the westerly and easterly periods. In the easterly period, the mean diameter was smaller in the winter following El Niño when rainfall was smaller, and larger in the winter following La Niña when rainfall was larger. Rainfall variation could affect DSD directly during the easterly period. By contrast, during the westerly period, the mean diameter was larger in the El Niño year and smaller in the La Niña year. Scatter diagrams and histograms confirmed this relationship. Therefore, it is likely that during the westerly period (summer), the effect of the ENSO on rainfall amount was not significant, and the DSD was not influenced as in winter.

[19] This study demonstrates that seasonal and interannual DSD variation exists in the western tropical Pacific region. Both the monsoon and ENSO cycles influenced DSD in a systematic way. Our study gives a reliable basis for DSD variation from direct observation data, and may be helpful in discussion of the DSD variability observed by satellite sensors, such as the TRMM.

[20] **Acknowledgments.** The authors thank K. Nakamura and S. R. Nakamura of Belau Cares for their support during these long-term observations. We also thank M. H. Sadao, T. Baba, and T. Misawa in Palau for their help in maintaining the observation instruments, S. Okumura and his team at Global Ocean Development and the members of IORGC for their support during the observations, and T. Kozu at Shimane University for his valuable advice. The GFD Dennou Club library was used to draw the figures. The ENSO cycle index data used El Niño observations by the Japan Meteorological Agency.

References

Atlas, D., C. W. Ulbrich, F. D. Marks Jr., E. Amitai, and C. R. Williams (1999), Systematic variation of drop size and radar-rainfall relations, *J. Geophys. Res.*, *104*, 6155–6169.

Fujiwara, M. (1965), Raindrop-size distribution from individual storms, *J. Atmos. Sci.*, *22*, 585–591.

Gray, W., and R. Jacobson (1977), Diurnal variation of deep cumulus convection, *Mon. Weather Rev.*, *105*, 1171–1188.

Kozu, T., T. Shimomai, Z. Akramin, Marzuki, Y. Shibagaki, and H. Hashiguchi (2005), Intraseasonal variation of raindrop size distribution at Koto Tabang, West Sumatra, Indonesia, *Geophys. Res. Lett.*, *32*, L07803, doi:10.1029/2004GL022340.

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. Meteorol. Soc. Jpn.*, *84A*, 195–209.

Kubota, H., R. Shirooka, T. Ushiyama, T. Chuda, S. Iwasaki, and K. Takeuchi (2005), Seasonal variations of precipitation properties associated with the monsoon over Palau in the western Pacific, *J. Hydrometeorol.*, *6*, 518–531.

Murakami, T., and J. Matsumoto (1994), Summer monsoon over the Asian continent and western North Pacific, *J. Meteorol. Soc. Jpn.*, *72*, 719–745.

Nitta, T., and T. Motoki (1987), Abrupt enhancement of convective activity and low-level westerly burst during the onset phase of the 1988–89 El Niño, *J. Meteorol. Soc. Jpn.*, *65*, 165–171.

Rao, T. N., D. N. Rao, K. Mohan, and S. Raghavan (2001), Classification of tropical precipitating systems and associated *Z-R* relationships, *J. Geophys. Res.*, *106*, 17,699–17,712.

Reddy, K. K., and T. Kozu (2003), Measurements of raindrop size distribution over Gadanki during south-west and north-west monsoon, *Indian J. Radio Space Phys.*, *32*, 286–295.

Ropelewski, C. F., and M. S. Halpert (1987), Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation, *Mon. Weather Rev.*, *115*, 1606–1626.

Stout, G. E., and E. A. Mueller (1968), Survey of relationships between rainfall rate and radar reflectivity in the measurement of precipitation, *J. Appl. Meteorol.*, *7*, 465–474.
Sui, C.-H., K.-M. Lau, Y. N. Takayabu, and D. A. Short (1997), Diurnal variations in tropical oceanic cumulus convection during TOGA COARE, *J. Atmos. Sci.*, *54*, 639–655.
Tokay, A., and D. A. Short (1996), Evidence from tropical raindrop spectra of the origin of rainfall from stratiform versus convective clouds, *J. Appl. Meteorol.*, *35*, 355–371.
Tokay, A., D. A. Short, C. R. Williams, W. L. Ecklund, and K. S. Gage (1999), Tropical rainfall associated with convective and stratiform clouds: Intercomparison of disdrometer and profiler measurements, *J. Appl. Meteorol.*, *38*, 302–320.
Yuter, S. E., and R. A. Houze Jr. (1997), Measurements of raindrop size distributions over the Pacific warm pool and implications for Z-R relations, *J. Appl. Meteorol.*, *36*, 847–867.

K. Krishna Reddy, H. Kubota, R. Shirooka, T. Ushiyama, and K. Yasunaga, Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan. (tushi@affrc.go.jp)