Raindrop Spectra at the Ground

DOUGLAS M. A. JONES
Champaign, Illinois

17 July 1990 and 13 February 1992

ABSTRACT

Volume samples of raindrop spectra (26 865 m^3) recorded at ten widely dispersed sites from the tropics to the Aleutian Islands yielded spectra with dominant modes in the range 0.8–1.6 mm. Peaks at the 0.9-mm diameter were found but were not significantly more frequent than other nearby sizes. Secondary peaks in the averaged spectra were detected for some rain-rate and site combinations but not uniformly in all samples.

This study provides an indication of the limits of the extent to which local peaks, resulting from size preferences during drop breakup, could be expected to be seen in data obtained with instruments of limited sample volumes.

1. Introduction

Brown (1988), List et al. (1987), and List (1988) have derived raindrop spectra for collision–coalescence precipitation using equations from Low and List (1982a,b). The derived spectra display modes at approximately 0.3, 0.8, and 1.8 mm in diameter after sufficient time has elapsed for the spectra to stabilize. Similarly, Valdez and Young (1985), using a Markov chain model, noted three peaks in their equilibrium distributions, 0.24, 0.87, and 2.0 mm.

The physical data cited to substantiate existence of the modes calculated by List were collected in the tropics by List (1988) with an electro-optical spectrometer measuring drops of diameter 0.045–0.96 mm and with the Joss–Waldvogel (J–W) disdrometer (1967). The J–W disdrometer is expected to measure raindrop diameters from 0.35 through 5.0 mm. The volume sampled is a function of the droplet terminal velocity. In the range of drop diameters measured by the instrument, the maximum volume sampled is 2.7 m^3. List modified the disdrometer to avoid the dead time designed into the instrument. This dead time effectively eliminates drop diameters smaller than 1 mm as the rainfall rates increase above an unspecified rate. Using the two instruments, List (1988) found modes near 0.3, 0.9, and 1.9 mm. In addition, Steiner and Waldvogel (1987) reviewed 1271 1-min samples collected with the J–W disdrometer to find distinct peaks in the sample distributions at 0.7, 1.0, 1.9, and possibly 3.2 mm. Since the publication of these papers, Sheppard (1990) has discussed an artifact in the classification by size of drops impacting the J–W disdrometer such that there could be overlapping in the assignment of drop sizes. This artifact could initiate artificial modes at 0.6–0.7, 1.0–1.2, and 1.8 mm in diameter in the distributions measured by the device.

2. Description of ISWS raindrop data

The raindrop spectra collected between 1953 and 1968 by the Illinois State Water Survey (ISWS) provide independent evidence to examine the presence of peaks in the distributions. The spectra were obtained using an automated camera system developed to record raindrop images for the determination of radar reflectivity. This system covered a range of drop sizes similar to the J–W disdrometer but had no upper size limit beyond that imposed by the frequency of appearance of sufficient drops in each size interval to adequately describe the parent distribution. In contrast to the disdrometer systems that sense the arrival of raindrops at a plane, the ISWS camera sensed the raindrops within a volume of space at an instant in time. (The disdrometer measures rainfall rate directly in that it senses the arrival of drops at a plane. Radar reflectivity is calculated by accounting for the terminal velocity of the several classes of raindrop sizes. The camera measured volume distribution from which reflectivity is directly obtained, but the rainfall rate must be calculated using assumed terminal velocities of the raindrops.) The camera imaged without parallax the two-dimensional shape of the falling drops, as viewed horizontally, about 1.5 m above the ground. Approximately 0.143 m^3 of space was recorded at each exposure, defined by the 35.6-cm optical depth of field and the 73.7-cm diameter optical field stop. A cubic-meter volume was obtained from seven negatives ex-

---

Corresponding author address: Douglas M. A. Jones, 1505 Paula Dr., Champaign, IL 61821-1531.

TABLE 1. Description of spectra collection sites.

Collection site	Latitude, longitude	Elevation (m)	Collection dates	Number of cubic-meter samples
Central Illinois	40°11′N, 88°43′W	223	16 Jul 1953–3 Jan 1955	1211
			1 May 1964–22 Sep 1964	1119
Miami, Florida	25°49′N, 80°17′W	2	20 Aug 1957–14 Aug 1958	2506
Corvallis, Oregon	44°34′N, 123° 15′W	67	19 Dec 1957–28 Jun 1958	1703
Woody Island, Alaska	57°47′N, 152°20′W	15	30 Aug 1959–14 Aug 1960	2688
Majuro, Marshall Islands	7°5′N, 171°23′E	3	11 Mar 1959–29 Apr 1961	2552
Bogor, Indonesia	6°30′S, 106°48′E	260	31 Dec 1959–10 Apr 1961	1879
Franklin, North Carolina	35°2′N, 83°28′W	1360	21 Dec 1960–25 Mar 1962	4804
Island Beach, New Jersey	39°52′N, 74°5′W	8	30 Oct 1960–24 May 1962	3147
Flagstaff, Arizona	35°2′N, 111°52′W	2235	18 Jul 1966–10 Aug 1966	381
			9 Jul 1967–19 Aug 1967	1514
Panama Canal Zone	9°16′N, 80°0′W	3	27 Jun 1968–25 Nov 1968	3361

posed within 10.5 s; the camera was usually idle for the remaining 49.5 s of each minute. The 1.5 s between each exposure was sufficient to ensure that all detectable drops were clear of the photographed volume before the next exposure was made. The falling raindrops were rendered motionless on the film by a flash duration of 10 μs. Data collection was initiated manually or by a switch activated by the tip of a bucket unstable at 0.025

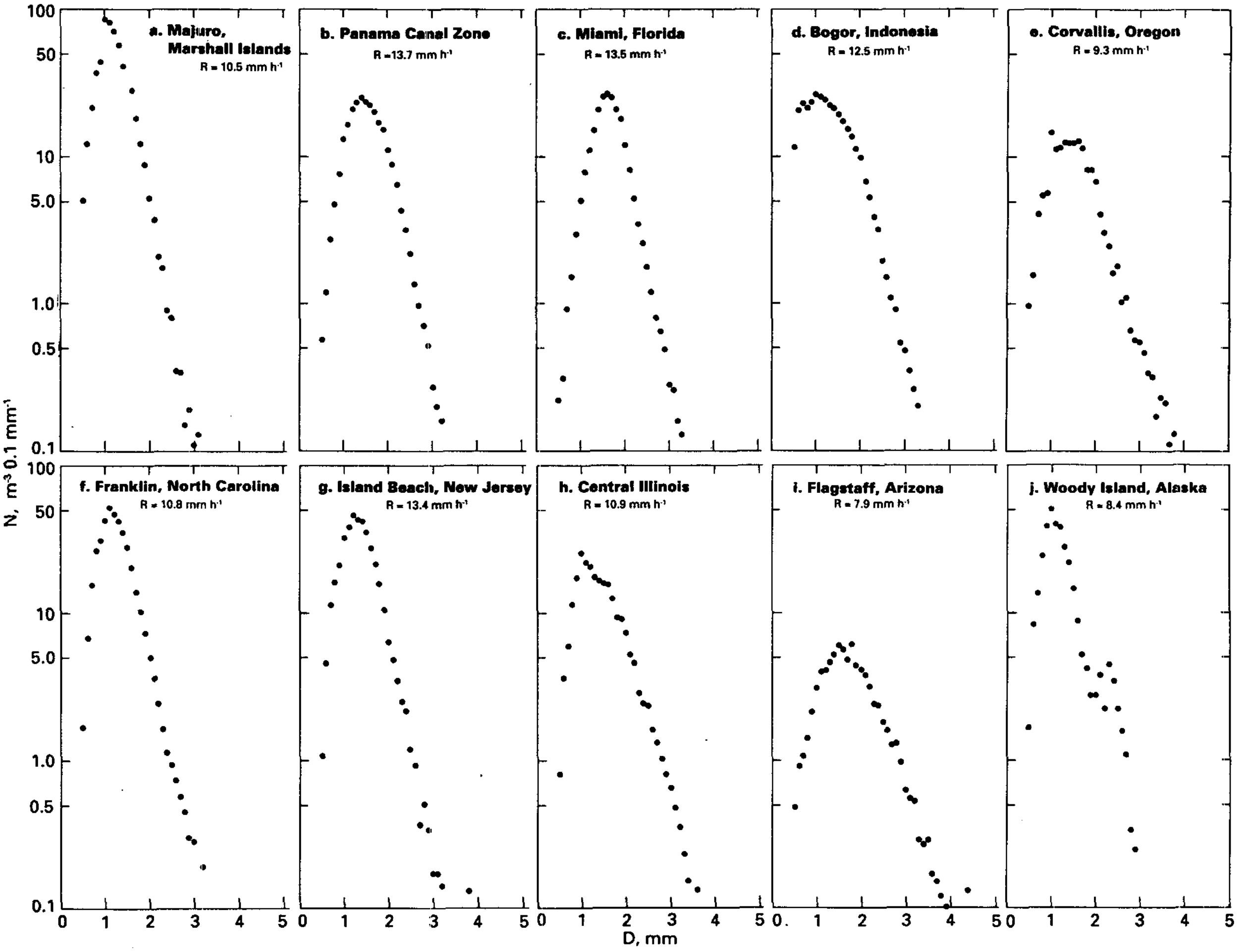

FIG. 1. Raindrop diameter number distributions for ten sites for rainfall rates near 10 mm h^{-1}.

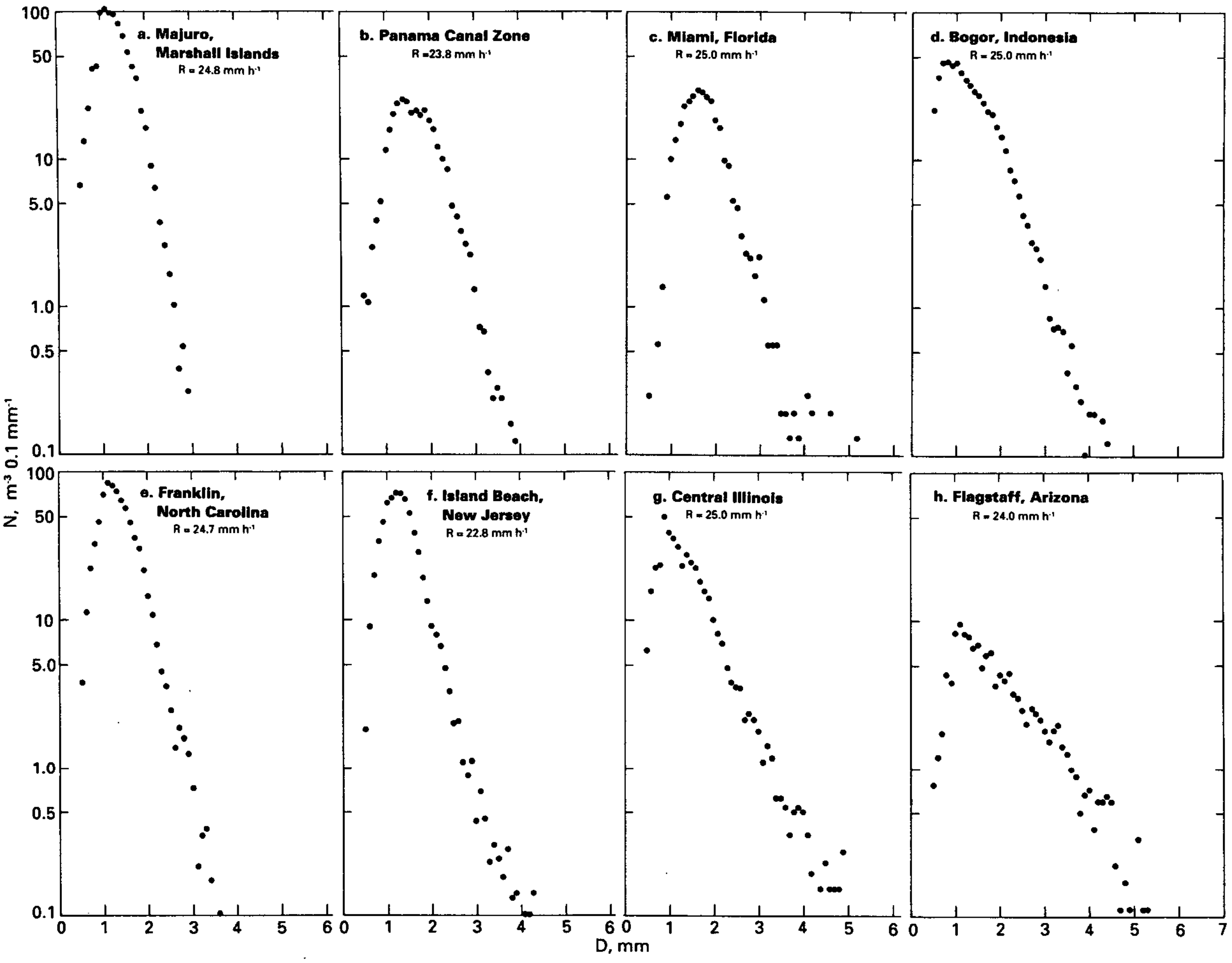

FIG. 2. Raindrop diameter number distributions for eight sites for rainfall rates near 25 mm h^{-1}.

cm of liquid-precipitation depth. Data collection ceased when a tip was not sensed during a 10-min interval. Samples (sequence of seven exposures) containing less than eight drop images, or a calculated rainfall rate less than 0.1 mm h^{-1}, were not included in the dataset. A 3048-cm spool of 70-mm film had a capacity for 72 min of data, after which the film magazine was manually replaced. Although a number of storms were recorded on more than one spool of film, many were terminated after 72 min of data were collected.

Data collection is summarized in Table 1. The data from Flagstaff, Arizona, are limited to two summers and that from Panama to 5 months; all other sites include at least 1 year of operation. The total number of spectra collected was 26 865.

Drops smaller than 0.5 mm in diameter were too small to be detected and measured properly by the camera recording system. Drops were measured with a precision of ±0.1 mm. In order to determine the accuracy of the measured drop sizes, repetitive measurements of some of the data from Miami, Florida, were made by several different analysts. For drops 0.8 mm and larger, the repetitions showed agreement in the number of drops in each 0.1-mm size class to ±10%. Also, rainfall rates calculated from spectra collected simultaneously with open-scale weighing-bucket raingage records were found to agree to 5%.

Rinehart (1983) has suggested that wind sorting of the imaged drops may have occurred, particularly when the ambient wind was blowing along the optical axis of the camera. This possibility was addressed in the orientation of the photographed volume by placing the optical axis orthogonal to the prevailing wind. This would minimize sorting in the larger drops. Such an orientation would not eliminate wind sorting entirely since the bulk of the camera is an obstacle in the wind field and will distort the wind flow around it, with the major effect on the smaller drops. Quantification of this sorting effect was not attempted.

Another source of possible error is that introduced

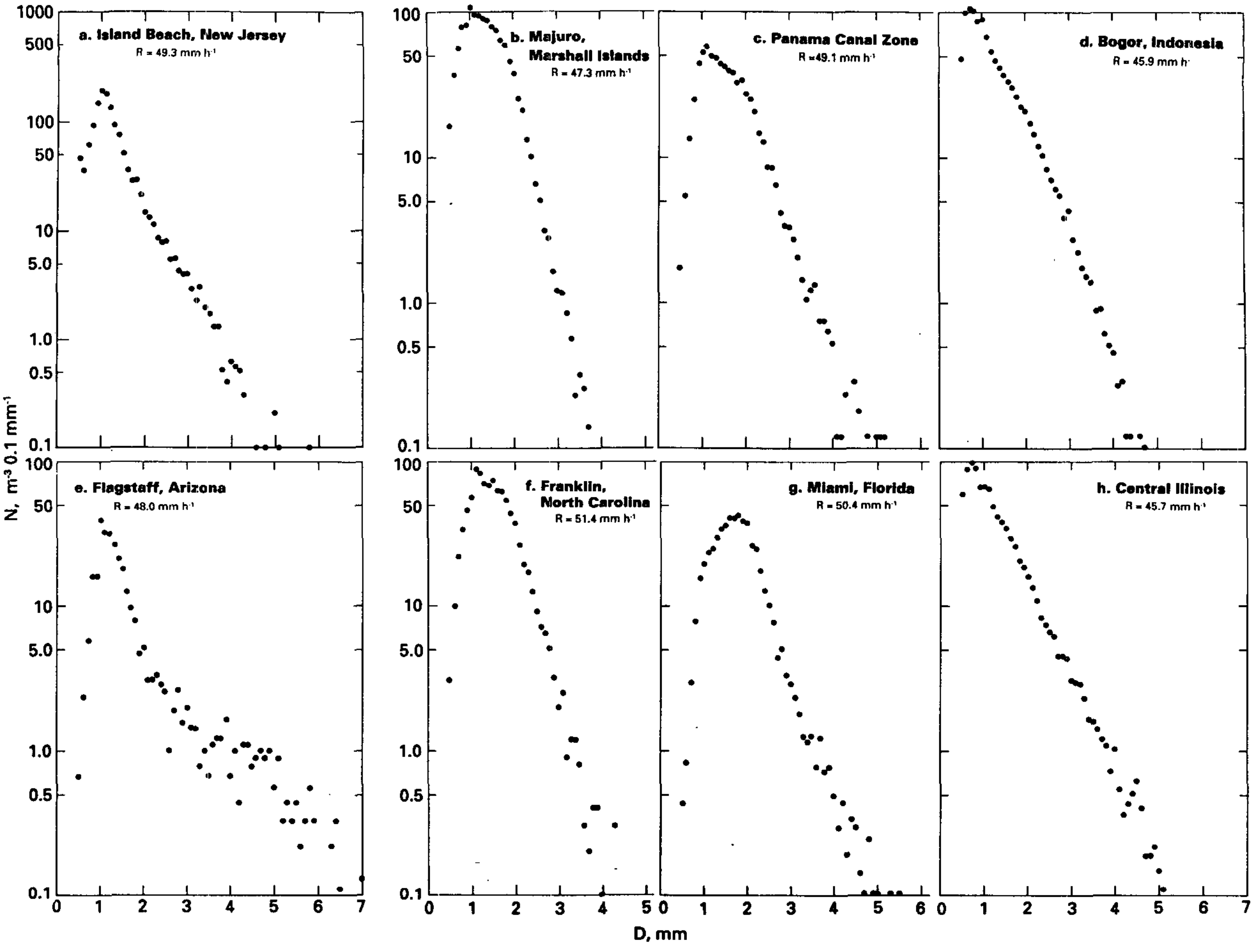

FIG. 3. Raindrop diameter number distributions for eight sites for rainfall rates near 50 mm h^{-1}.

by drops splashing or dripping from the metal shields that define the photographed volume. In the final version of the camera, used after 1956, these shields consisted of 32" radius inverted U shapes. During the operation of the camera at Flagstaff in 1967, fine-meshed screening was added to the upper surfaces of the shields. Comparisons made of spectra collected before and after the shield modifications revealed no splash effect in the data.

There is a possibility that a large intervening drop may obscure another drop occupying space with the larger drop on an optical ray path. Such a possibility is very remote since only a few percent of the area photographed was occupied by drops even in the heaviest rains.

The raindrop images were measured manually by matching their major and minor axes to the transparent jaws of special calipers. Rotation of a lead screw moved the jaws in or out and turned integral switches to generate numbers corresponding to the jaw spacing. The two dimensions were averaged for approximations of the equivalent spherical diameters.

3. Results

Plots of the average raindrop number distributions for each site, at a rainfall rate of approximately 10 mm h^{-1}, are shown in Figs. 1a–j. At least 10 m^3 of data were averaged to obtain each of the distributions. The largest number of drops in any diameter interval appears to vary between 0.9 mm for Woody Island, Alaska (Fig. 1j), and 1.6 mm for Miami (Fig. 1c). There is a hint of a mode at the 1-mm diameter in the paper by Marshall and Palmer (1948), even though their data were summarized in 1-mm size intervals and their smallest interval is from 0.5 to 1.4 mm.

In Figs. 2a–h are raindrop spectra for intensities near 25 mm h^{-1} for all sites that had rates this intense. Woody Island and Corvallis, Oregon, had too few or no rates that would allow average spectra at 25 mm h^{-1} to be calculated. The other sites may by classified by modal diameter at this rainfall rate into Bogor, Indonesia, and central Illinois near 0.8 mm; Flagstaff, Franklin, North Carolina, Majuro, Marshall Islands, and Island Beach, New Jersey, with mode near the

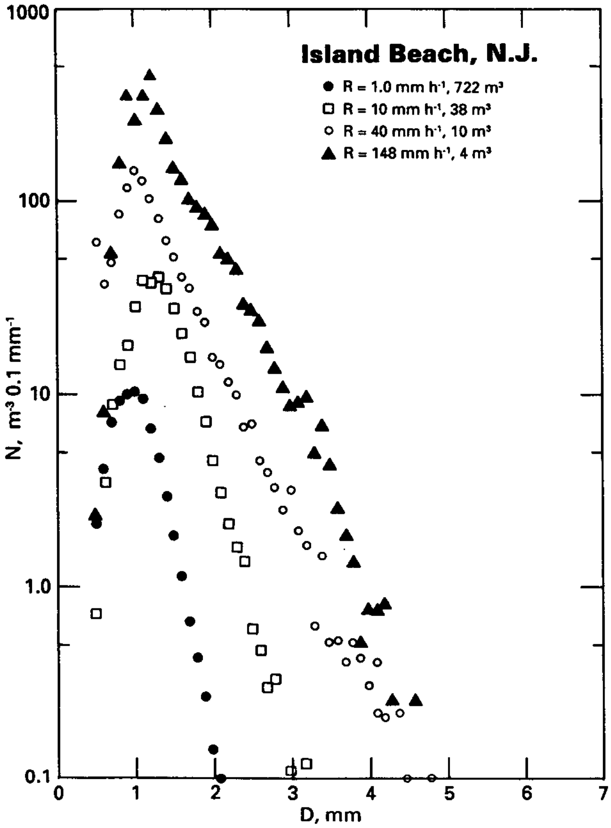

FIG. 4. Raindrop diameter number distributions for Island Beach, New Jersey, for rainfall rates of 1, 10, 40, and 148 mm h^{-1} illustrating modal shift with increasing rainfall rate noted at some sites.

1.1-mm diameter; and Miami and Panama with mode near the 1.5-mm diameter. Perhaps Miami and certainly Panama have secondary peaks near the 1.9-mm diameter.

Figures 3a–h display raindrop spectra for average rates near 50 mm h^{-1} for all sites that experienced rates of this magnitude. The data from the sites may be partitioned into three categories: Miami with a mode at the 1.8-mm diameter; Illinois and Bogor with a mode at the 1.7-mm diameter; and Flagstaff, Island Beach, Majuro, Franklin, and Panama with a mode at the 1.0–1.1-mm diameter. A weak secondary peak appeared near the 3.5–4.0-mm diameter at Miami, Flagstaff, and the Panama Canal Zone.

The variation of spectral shape with rain intensity was not the same for all sites. At some sites, the predominant mode was observed to shift to larger diameters as the rainfall rate increased above 10 mm h^{-1} and returned to smaller diameters at very large rainfall rates (>50 mm h^{-1}). This is illustrated in Fig. 4 with spectra for four rainfall rates from Island Beach. In contrast, the Miami spectra had a modal diameter of 1.1 mm at the lowest rates, shifting to 2.0 mm at the highest rates. The spectra recorded at Majuro had only insignificant departures from a modal diameter of 1.0 mm at all average rainfall rates up to 200 mm h^{-1}.

The data discussed above are average spectra collected within a narrow range of rainfall rates calculated from the spectra. The range of rates was ±1.0 mm h^{-1} about each specified rate. It is possible that the combining of spectra from many rains, although at the same rainfall rate, may mask features in the individual spectra. Insight may be gained on the severity of this problem by examining the few datasets that were collected while the camera was sampling 4 m^3 min^{-1} instead of the normal 1 m^3 min^{-1} or by selecting consecutive datasets from periods of steady rain.

There were several rains in the Panama Canal Zone during which the camera was operated to obtain 4 m^3 each minute in nonthunder, showery conditions. The combined sample from 10 m^3 collected over a continuous 2.5-min interval is listed in Table 2. Although a smooth distribution of droplet sizes is approached for diameters less than 2 mm, it is obvious that there is a large degree of irregularity within the long tail of the distribution for the larger sizes. This is due mainly, in this case, to the small numbers of drops per size interval.

The other procedure to obtain a large sample size is done by combining contiguous 1 m^3 min^{-1} samples in steady rain. A spectrum for 28 m^3 from Majuro is listed in the second column of Table 2. This is a narrow and smooth distribution of drop sizes from a low rainfall rate, with a mode at 0.9 mm. A second spectrum from Majuro at a smaller rainfall rate is listed in the third column of Table 2. This 12-m^3 sample has a secondary peak at the 1.8-mm-diameter droplet size, but due to the small number of drops at that size, the peak is of questionable significance (the difference between adjacent intervals within one standard deviation of the variability expected from Poisson frequency distributions). These examples illustrate that averaging of larger volumes is indeed necessary and that even samples of approximately 10 m^3 do not yield significant definitions of secondary peaks at large (>1.5 mm) drop sizes.

In addition, a search was made of the Island Beach dataset to locate spectra that would most nearly meet the equilibrium development criteria of List (1988). Nine datasets with at least 10 m^3 samples from steady rain were selected. The selection process limited the sets to those obtained at relatively low rainfall rates (less than 12 mm h^{-1}) in weather conditions in which warm, moist airstreams were overrunning colder air. In order to establish a criterion to compare the sampled spectra with a standard distribution, each dataset was fitted by a lognormal distribution. For these datasets, the distributions peaked near the 1.0-mm diameter. Deviations from the lognormal distributions at each size interval were examined for each 1 m^3 spectrum. Most size intervals greater than the 0.8-mm diameter were randomly distributed about their respective log-

TABLE 2. Three unaveraged spectra.

Drop diameter (mm)	Panama Canal Zone 10 August 1966 1559–1601 LST	Majuro, Marshall Islands 25 April 1959 0706–0733 LST	Majuro, Marshall Islands 16 May 1959 0820–0831 LST
0.5	0	112	40
0.6	3	370	70
0.7	7	1036	109
0.8	18	1576	134
0.9	26	2010	137
1.0	116	1543	154
1.1	134	930	140
1.2	157	538	110
1.3	180	308	73
1.4	166	174	52
1.5	141	118	38
1.6	118	67	23
1.7	109	42	10
1.8	78	17	16
1.9	37	8	4
2.0	41	6	6
2.1	31		2
2.2	23		0
2.3	27		4
2.4	29		1
2.5	22		1
2.6	26		1
2.7	13		
2.8	20		
2.9	13		
3.0	16		
3.1	22		
3.2	9		
3.3	3		
3.4	13		
3.5	7		
3.6	10		
3.7	6		
3.8	4		
3.9	9		
4.0	4		
	$n = 10$ m^3 Rate = 34 mm h^{-1}	$n = 28$ m^3 Rate = 3 mm h^{-1}	$n = 12$ m^3 Rate = 1 mm h^{-1}

normal distributions. However, three singularities in seven of the nine spectra were noted. The smallest diameter with a singularity was at 0.9 mm, which was found to have *fewer* drops than the lognormal distribution. A singularity of a *larger* number of drops with respect to the standard was found at the 1.7-mm diameter. A *smaller* number of drops in the spectra as compared to the standard was found at the 2.1-mm diameter.

4. Discussion

Volume (1-m^3) samples of raindrop spectra (26 865 m^3) recorded at ten widely dispersed sites from the tropics to the Aleutian Islands yielded spectra with dominant modes in the range 0.8–1.6 mm. Peaks at the 0.9-mm diameter were found but were not significantly more frequent than other nearby sizes.

Secondary peaks in the averaged spectra were detected for some rain-rate and site combinations but not uniformly in all samples.

Overall, these data do not provide clear evidence for the predominance of drops at 0.9- or 1.9-mm sizes, but this could be due, on the one hand, to the fact that individual samples (1 m^3) were of insufficient size to yield statistically significant indications of peaks at large drop sizes or, on the other hand, to the inherent smoothing involved in averaging samples from a range of different meteorological conditions.

This study provides an indication of the limits of the extent to which local peaks, resulting from size preferences during drop breakup, could be expected to be seen in data obtained with instruments of limited sample volumes. The expectation that the local peaks seen in data from the Joss–Waldvogel disdrometers can be confirmed in the data obtained with the photographic techniques was not fulfilled, but neither was a clear negation of these results indicated.[1]

REFERENCES

Brown, P. S., Jr., 1988: The effects of filament, sheet, and disk breakup upon the drop spectrum. *J. Atmos. Sci.,* **45,** 712–718.

Joss, J., and A. Waldvogel, 1967: Ein spektrograph fuer niederschlagstropfen mit automatischer auswertung. *Pure Appl. Geophys.,* **68,** 240–246.

List, R., 1988: A linear radar reflectivity–rainrate relationship for steady tropical rain. *J. Atmos. Sci.,* **45,** 3564–3572.

——, N. R. Donaldson, and R. E. Stewart, 1987: Temporal evolution of drop spectra to collisional equilibrium in steady and pulsating rain. *J. Atmos. Sci.,* **44,** 362–372.

Low, T. and R. List, 1982a: Collision, coalescence, and breakup of water drops at terminal velocity. Part I. *J. Atmos. Sci.,* **39,** 1591–1606.

——, and ——, 1982b: Collision, coalescence, and breakup of water drops at terminal velocity. Part II. *J. Atmos. Sci.,* **39,** 1607–1618.

Marshall, J. S., and W. McK. Palmer, 1948: The distribution of raindrops with size. *J. Meteor.,* **5,** 165–166.

Rinehart, R. E., 1983: Out-of-level instruments: Errors in hydrometeor spectra and precipitation measurements. *J. Appl. Meteor.,* **22,** 1404–1410.

Sheppard, B. E., 1990: Effect of irregularities in the diameter classification of raindrops by the Joss–Waldvogel disdrometer. *J. Atmos. Oceanic Technol.,* **7,** 180–183.

Steiner, M., and A. Waldvogel, 1987: Peaks in raindrop size distributions. *J. Atmos. Sci.,* **44,** 1327–1333.

Valdez, M. P., and K. C. Young, 1985: Number fluxes in equilibrium raindrop populations: A Markov chain analysis. *J. Atmos. Sci.,* **42,** 1024–1036.

---

[1] The camera datasets are available on 6250-bit, 0.5″ magnetic tape, ASCII, 80 length records, 8000 block size. Enquiries should be addressed to: Chief, Illinois State Water Survey, Support Services, 2204 Griffith Dr., Champaign, IL 61820.