NOTES

Raindrop Sizes and Related Parameters for GATE

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ABSTRACT

Several sets of drop size measurements were made on ships and aircraft during GATE. The data were taken primarily as support for the radar measurements and have been analyzed to provide relations between radar reflectivity and desired meteorological quantities.

Uncertainties in the results because of instrumental difficulties and differences within and between the various data sets are examined and discussed. The overall Z-R relation based on the combined data sets is $Z=180R^{1.35}$. Also included are relations of the reflectivity factor to rainwater content and attenuation of 5 cm radiation.

Comparison of the drop size distributions with measurements from other places suggests that tropical oceanic showers typically contain an abundance of medium-sized drops and relatively few large ones.

1. Introduction

This note summarizes the results of several sets of drop size measurements made on shipboard and on aircraft during GATE. They were taken primarily as support for the quantitative radar measurements since interpretation of measured radar reflectivities in terms of precipitation rates or water contents requires knowledge or assumptions about the raindrop size spectra.

In addition to applications to radar, observations of raindrop size distributions are important for cloud physics studies; they provide insight into the processes of hydrometeor development and data for checking results of theoretical computations. In this study, characteristics of the raindrop spectra in the GATE area are considered and empirical expressions relating radar reflectivity to rainfall rate, water content and attenuation of 5 cm radiation are given.

2. Shipboard measurements

There were three Joss disdrometers located on ships during all or part of the GATE experiment. The names of the ships, the times during which data were taken, and the organizations responsible for taking and analyzing the data are listed in Table 1. Locations of the ships are shown in Fig. 1. The disdrometers on all the ships were activated manually. On *Gilliss* and *Researcher* they were turned on only when moderate-to-heavy showers occurred while the University of Toronto disdrometer was activated whenever any rain fell, and the Toronto records include many hours of light rain as well as the relatively brief periods of heavier rain.

The Joss disdrometer is a momentum exchange device which converts the vertical momentum of any raindrop striking the sensor to an electrical pulse whose magnitude can be recorded. The sensor is

TABLE 1. Summary of shipboard data taken with Joss disdrometers.*

Ship	Data collected Phase 1	Phase 2	Phase 3	Sample size	Collected and analyzed by
Researcher	114 min on 4 days	76 min on 2 days	30 min on 2 days	2 min	NHEML, Miami
Gilliss	76 min on 2 days	66 min on 3 days	78 min on 3 days	1 min	Dept. of Meteorology, MIT
Dallas	774 min on 6 days			2 min	Dept. of Physics, Univ. of Toronto
Fay			764 min on 7 days	2 min	Dept. of Physics, Univ. of Toronto

* Data from the *Researcher* and *Gilliss* are restricted to moderate and heavy rain; data from *Dallas* and *Fay* include many hours of light or very light rain.

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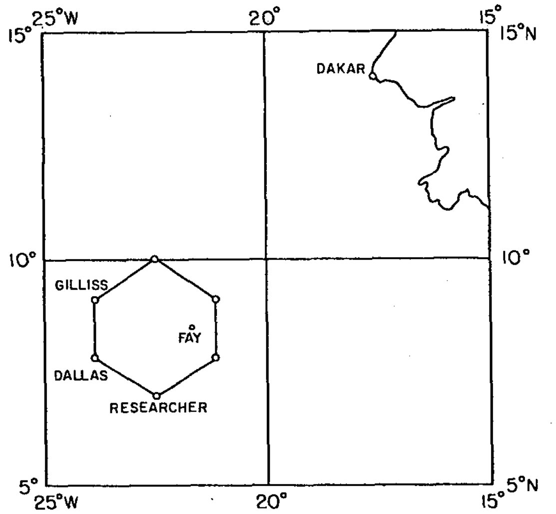

FIG. 1. Positions of ships at times when drop size measurements were made.

50 cm^2 in area and samples $\sim$2 m^3 min^{-1} depending on the fall velocities of the raindrops. The size range of the drops which can be measured is from $\sim$0.4 mm in diameter to greater than 5 mm. Resolution, in increments of drop diameter, increases from 0.1 mm for the small drops to 0.3 mm for the large ones.

The disdrometer can respond to sound waves as well as to the impact of raindrops; for this reason it has a noise suppression circuit which adjusts the threshold of sensitivity according to the level of environmental noise. The effect of this circuit is to place a lower limit (which varies with changes in the noise intensity) on the size of the drops which can be detected. Measurement of drops with signals large enough to exceed the threshold is not affected in any way. The noise level on the ships was so high that most of the drops $<$1.5 mm in diameter were suppressed in the measurements. In the case of the disdrometer on *Gilliss*, drops up to 2 mm in diameter were seriously affected.

The performance of the disdrometer might also be affected by the motion of the ships, either by changing the momentum of the drops relative to the sensor or modifying the effective sampling area as it tilts. Calculations indicated that the effects would probably not be significant. If anything, they would have a slight tendency to broaden the observed spectra.

The first step in the analysis of the disdrometer data was an attempt to assess and correct for the effects of underestimating the number of small drops. Calibrations of the disdrometers before and after GATE indicated that the sizing is accurate to $\sim$3% of the diameter or 10% of the rainfall rate. The reliability of the calibrations is supported by the fact that when raingage and disdrometer data have been taken simultaneously on land in relatively quiet environments, the indicated rainfall amounts generally agree to within 10%. In correcting for the noise-suppression effects in GATE, therefore, it was assumed that the measurements of large drops were reliable but that small drops should be added to all measured distributions in a manner which satisfies the following criteria:

1) The corrections applied for each instrument

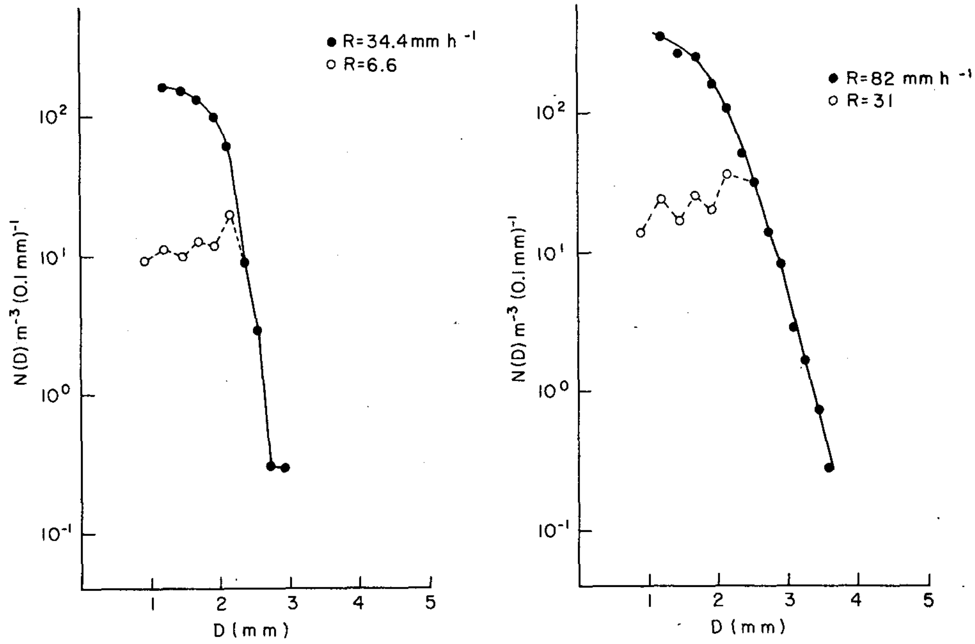

FIG. 2. Examples of drop size distributions from the *Gilliss* disdrometer before (○) and after (●) corrections were applied.

should be consistent throughout the experiment, i.e., the noise pattern for each ship is assumed to be relatively unchanging.

2) The corrected drop size distribution curves should be reasonably smooth and of a shape similar to ones measured elsewhere under less noisy conditions.

3) The total rain indicated by each disdrometer should be in good, or at least fair, agreement with the amount measured by the gages on the ship.

Before applying any correction, a requirement was imposed that every sample should contain at least 100 drops. Samples which were taken in relatively light rain and contained fewer than 100 drops were combined sequentially until the required number of drops was reached.

A correction scheme which satisfied the criteria was developed by trial and error. The measured drop numbers in all of the samples for drop size categories with 1 mm$<D<$2 mm, where D is the drop diameter, were then multiplied by the chosen correction factors. Some drop size distributions from the *Gilliss* data before and after corrections were applied are given in Fig. 2. A further addition ΔR was made to the computed rainfall rate to represent the contribution to R of drops with diameters between 0.4 and 1 mm. This addition as a function of rainfall rate was based on an empirical relation derived from disdrometer measurements in Panama showers, and varied from 17% of R at 5 mm h^{-1} to 8% for $R=100$ mm h^{-1}.

Corrections applied to the disdrometer data from the other ships were similar though not quite so drastic. Table 2 lists some comparisons between the rainfall amounts measured in GATE by the disdrometers (both before and after corrections were applied) and by the gages on the ships. The raingage on the *Gilliss* was immediately adjacent to the disdrometer. On the other ships, gages and disdrometers were within a few tens of meters of each other.

We recognize that the corrections which have been applied to the shipborne disdrometer data are disturbingly large. However, we have confidence in the resulting set of measurements because they are firmly anchored to the reliable measurements of large drops and are also generally in agreement with the gage data. Furthermore, direct comparison of radar-measured reflectivities with values derived from the *Gilliss* disdrometer showed good agreement (Geotis, 1978). Also, the characteristics of drop size distributions observed in GATE (after correction) are consistent with those of drop spectra observed in other tropical maritime regions (where no corrections were applied), as shown by the examples in Fig. 3. The spectra from Majuro Atoll in the Marshall Islands were observed by Mueller and Sims (1967) with a raindrop camera. The Panama drop size measurements were made by Geotis (1968) with a Joss disdrometer. A significant characteristic of the distributions in Fig. 3 is that they are very steep, with numerous drops in the range 1 mm$<D<$2 mm and relatively few drops with $D>$3 mm.

3. Airborne measurements

Drop samples near cloud base were collected with a foil impactor on the NOAA DC-6 aircraft as described by Cunning and Sax (1977a,b). A single sample was collected during each complete traverse of a cell or precipitation area. The sampling rate of the impactor is $\sim$30 ℓ s^{-1} and the cruising speed roughly 100 m s^{-1}. For a medium-sized convective element (dimension $\sim$3 km), then, a sample represents $\sim$1 m^3 of air.

A similar foil impactor was flown on one day on the NOAA C-130 aircraft at an altitude of $\sim$3 km. For this impactor, each sample represents 1.5 km of flight or 0.36 m^3 of atmosphere. The aircraft data are listed in Table 3 and examples of typical drop size distributions are in Fig. 4. The drop diameter categories used in analyzing the impactor data are 0.43 mm in width for the DC-6 and 0.22 mm for the C-130 measurements.

It can be noted from Figs. 3 and 4 that in contrast to the disdrometer and the C-130 impactor, the DC-6

TABLE 2. Rainfall amounts measured by gages and disdrometers.

Six-minute averages for 8 July 74: *Researcher*				Daily summaries: *Gilliss*					
	Siphon	Disdrometer				Gage amounts		Disdrometer	
Time	Gage (mm)	Indicated	Corrected	Date	Time	Wedge	Siphon	Indicated	Corrected
1745–1751	6.2	3.5	4.6	7 Jul	0319–0403		9.8	1.6	8.3
1751–1757	10.9	6.7	12.0	14 Jul	1255–1327	15.5	12.4	6.5	15.1
1757–1803	9.3	5.1	7.8	8 Aug	0856–0910		2.5	0.8	2.8
1803–1809	7.6	3.0	6.3	15 Aug	1548–1558	0.8		0.3	0.9
1809–1815	6.7	1.7	2.4	17 Aug	1941–2023	3.8		1.8	3.3
1815–1821	3.9	1.0	1.4	2 Sep	1449–1526	9.1		3.1	8.6
1821–1827	7.3	2.6	4.5	13 Sep	1934–2009	15.0		4.5	9.7
1827–1833	6.4	2.1	3.3	16 Sep	2200–2216	5.6		1.6	4.8
Total	53.8	24.7	42.3						

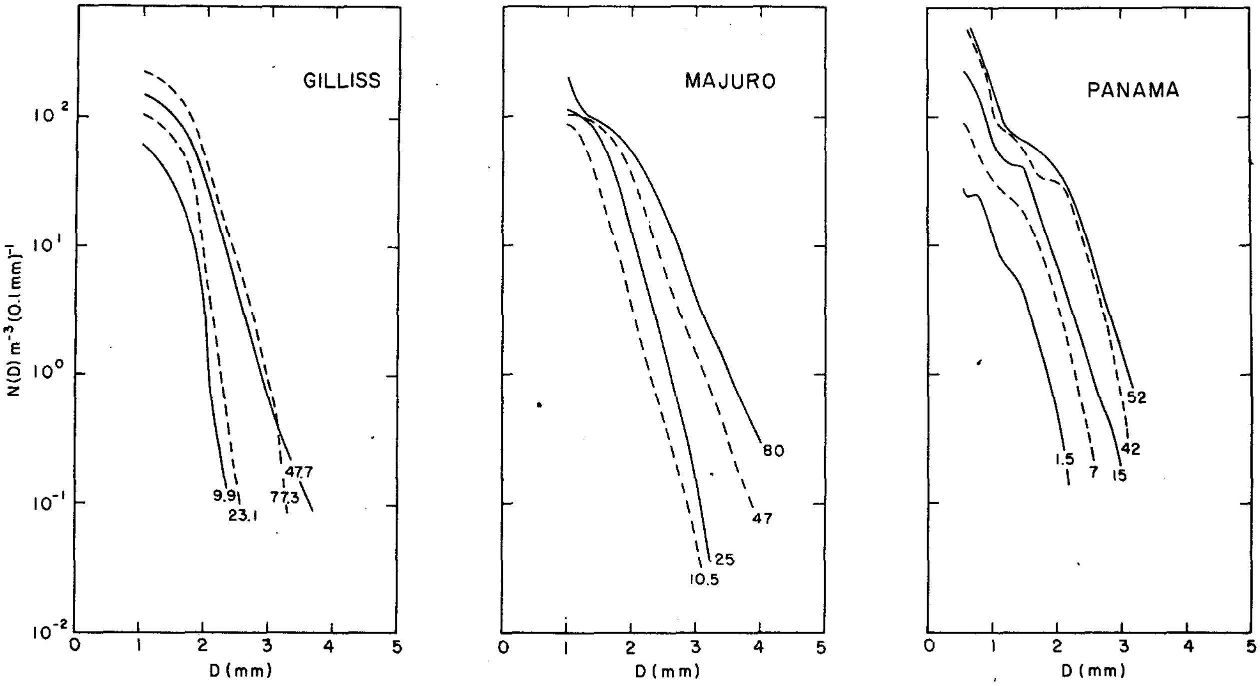

FIG. 3. Examples of averaged drop size distributions from various locations. [Majuro data from Mueller and Sims (1967); Panama data from Geotis (1968).]

impactor indicated significant numbers of drops with diameters in the 3–4 mm range, so that the drop size distributions from the DC-6 data are considerably less steep than those from the other instruments. The reasons for these differences are not known. Differences in the sampling mode, differences in resolution with respect to drop diameter and real differences in the distribution with height have been considered as possible explanations. Calculations of the probable effects of sampling mode and resolution indicate that they would not be large enough to explain the observed differences. Although dependence of drop size distributions on height might seem reasonable, the data do not support this hypothesis either, since no systematic variations with height are evident in the total data set.

TABLE 3. Summary of foil-impactor data, taken by NHEML on NOAA aircraft.

Date	Number of samples	Date	Number of samples
A. From NOAA DC-6, flight level 100–1000 m			
12 July	2	13 August	12
29 July	9	14 August	3
3 August	15	17 August	3
5 August	19	30 August	5
10 August	12	6 September	10
11 August	5	14 September	6
B. From C-130, flight level ∼3 km			
14 July	30		

4. *Z-R*, *Z-M* and *Z-A* relationships

From each measured and corrected drop size distribution the radar reflectivity factor Z and the rainfall rate R were computed by

$$\left.\begin{aligned} Z&=\sum_i \frac{(n_s)_i}{v_i}D_i^6 \\ R&=\frac{\pi\rho}{6}\sum_i (n_s)_i D_i^3+\Delta R \end{aligned}\right\}\text{[ship data]} \qquad \begin{matrix}(1)\\[2ex](2)\end{matrix}$$

and

$$\left.\begin{aligned} Z&=\sum_i n_i D_i^6 \\ R&=\frac{\pi\rho}{6}\sum_i n_i v_i D_i^3 \end{aligned}\right\}\text{[aircraft data]} \qquad \begin{matrix}(3)\\[2ex](4)\end{matrix}$$

where ρ is the density of water, v the terminal fall velocity of the drops, n the number of drops per unit volume and n_s the number of drops which strike the disdrometer surface per unit area per unit time. The summations are taken over the size categories for each instrument. We assume that drops with $D<1$ mm would not add significantly to the value of Z, an assumption supported by the Panama data.

For the *Gilliss* data, liquid water content and attenuation of 5.5 cm radiation were also computed.

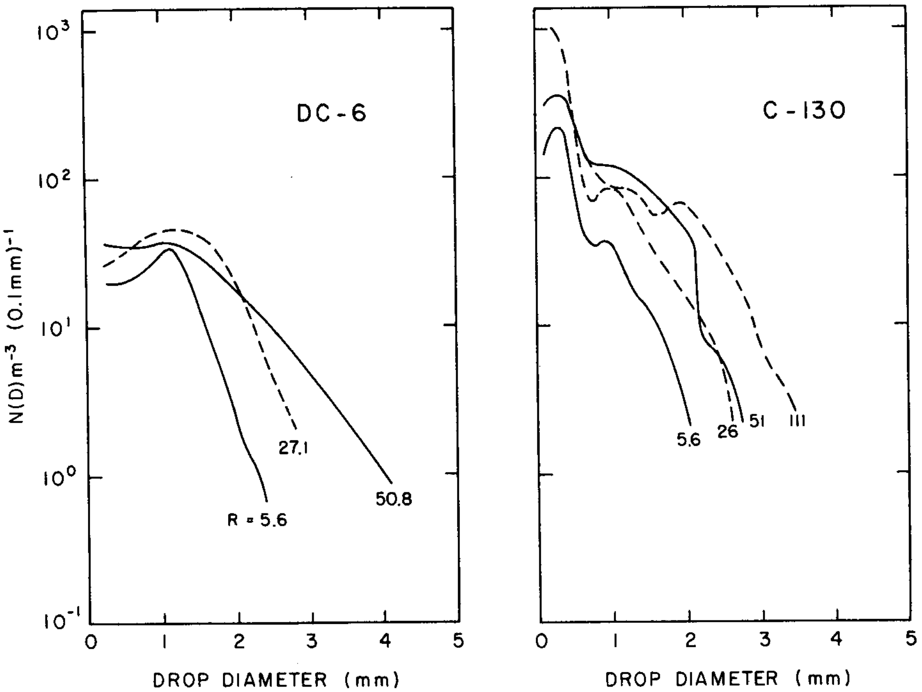

FIG. 4. Examples of drop-size distributions from foil impactor data. [DC-6 data from Cunning and Sax (1977a); C-130 data from Willis (1977, personal communication).]

The liquid water is given by

$$M=\frac{\pi\rho}{6}\sum_i \frac{(n_s)_i}{v_i}D_i^3+\Delta M \qquad (5)$$

and the two-way attenuation in decibels per unit length by

$$A=0.8686\sum_i \frac{(n_s)_i}{v_i}(Q_t)_i+\Delta A, \qquad (6)$$

where Q_t is the total attenuation (absorption plus scattering) cross section for each drop. The values of Q_t which were used are from Stephens (1962) for a temperature of 18°C. In (5) and (6) ΔM and ΔA represent contributions from drops with $0.4\ \text{mm}<D<1\ \text{mm}$. As with ΔR, ΔM was derived empirically from the Panama data. ΔA was computed from ΔM by assigning a diameter of 0.7 mm to all of the drops. Over the range of measurements ΔM varies from 30% of M at the low end where $M\approx 0.2$ g m^{-3} to 12% for $M\approx 4$ g m^{-3}. ΔA was about 25% of A at the low end of the range (where attenuation is negligible in any case) and less than 8% of A at the high end.

The rainfall-reflectivity points for all data are plotted in Fig. 5. The indicated line for Z (mm^6 m^{-3}) and R (mm h^{-1})

$$Z=180\,R^{1.35} \qquad (7)$$

represents a best-fit-by-eye relationship. This line is repeated in the plots of the individual data sets in Fig. 6.

There are noticeable differences in the average results from the different data sets. There were also apparently significant differences from day to day within the individual data sets, but the data base is not large enough for them to be examined statistically. We are not able to determine, therefore, the extent to which differences between the data sets are instru-

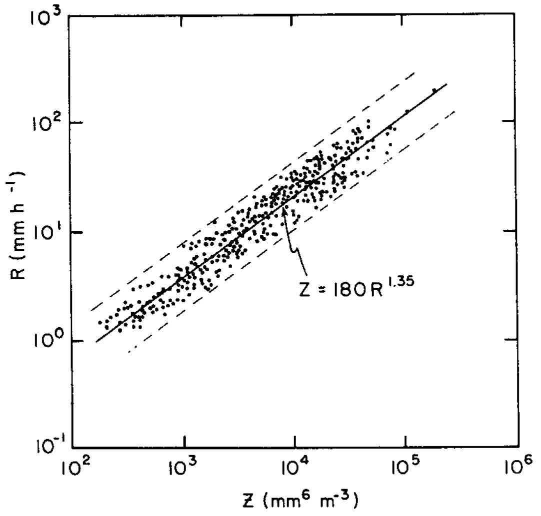

FIG. 5. Relation between rainfall rate and radar reflectivity factor for all data points. Lines show best fit by eye and region within a factor of 2 in rainfall.

mental, are related to sampling differences, or are related to differences in individual storms. For these reasons we have chosen to put all the data together, without bias, and to estimate therefrom the best-fit line in Fig. 5. It may be noted that the total scatter of the points about the line is contained within a factor of 2 in rainfall rate.

Z-M and *Z-A* relations based on the *Gilliss* data are shown in Figs. 7 and 8 together with the lines of best fit as judged by eye. For these calculations the data samples were grouped according to rainfall intensity.

The relations derived between Z and the various other quantities are summarized below:

$$Z=180\,R^{1.35},\qquad R=2.1\times10^{-2}\,Z^{0.74} \tag{8}$$

$$Z=7.4\times10^{3}\,M^{1.31},\qquad M=1.15\times10^{-3}\,Z^{0.76} \tag{9}$$

$$Z=2.7\times10^{5}\,A^{1.19},\qquad A=2.7\times10^{-5}\,Z^{0.84}. \tag{10}$$

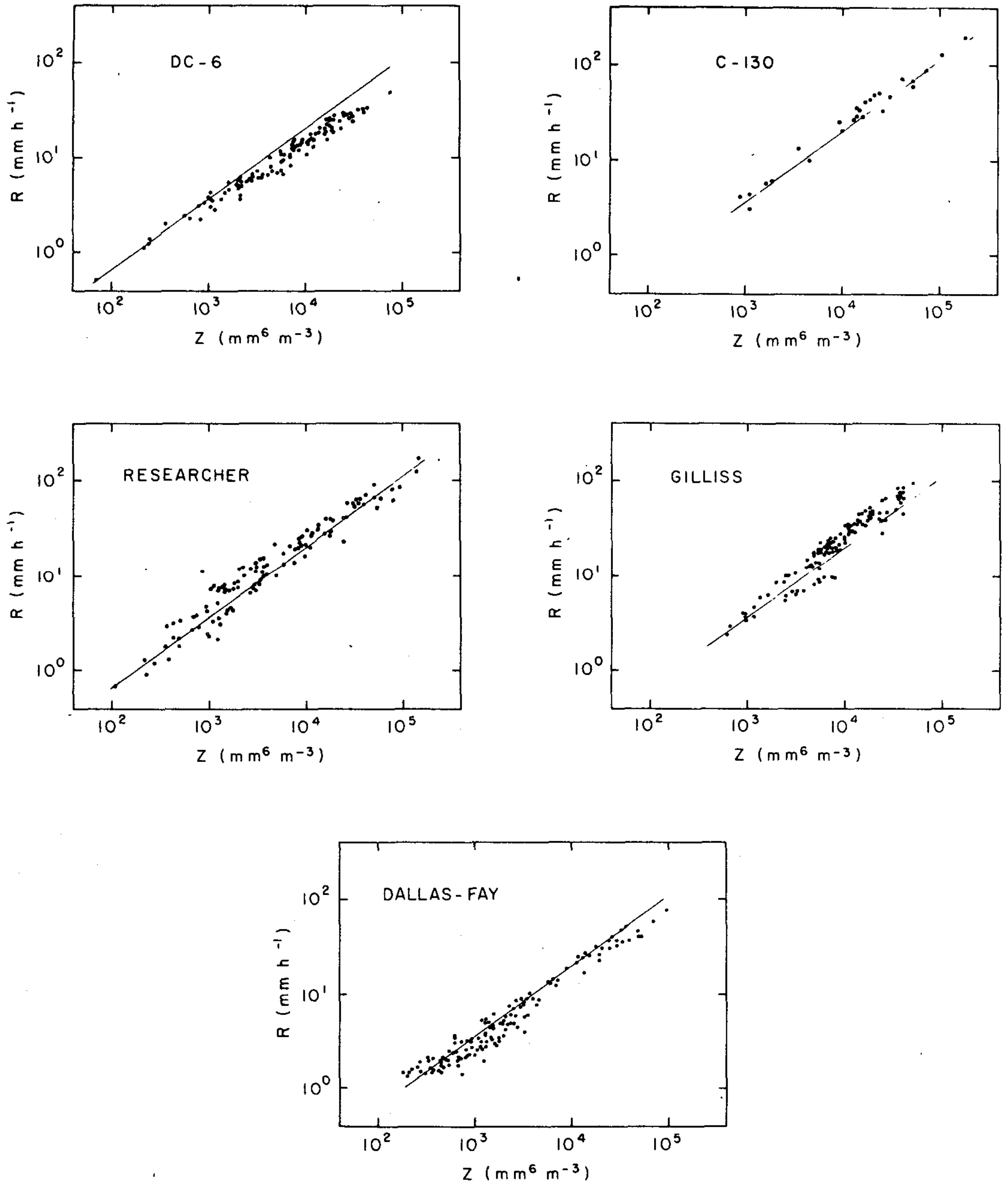

FIG. 6. Relation between rainfall rate and reflectivity for individual data sets. The overall best-fit line, $Z=180R^{1.35}$, is shown in each plot. [DC-6 and *Researcher* data points from Cunning and Sax (1977a); C-130 data points from P. Willis, personal communication; *Dallas* and *Fay* data points from J. Gillespie, personal communication.]

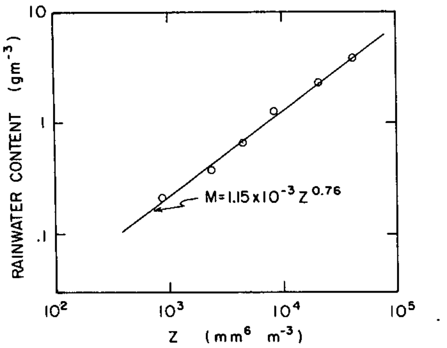

FIG. 8. Relation between reflectivity and two-way attenuation for 5.5 cm radiation, computed from *Gilliss* data grouped according to rainfall rate.

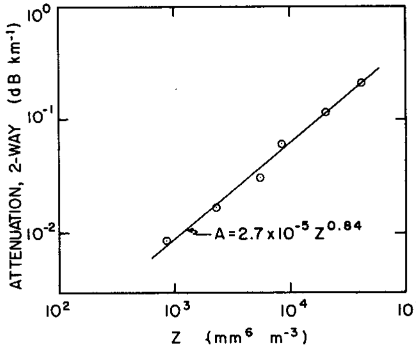

FIG. 7. Relation between reflectivity factor and rainwater content from *Gilliss* data grouped according to rainfall rate.

In (9) M is in g m^{-3}; in (10) A is in dB km^{-1} (two-way) and was calculated for a temperature of 18°C. The Z-R relation is based on all of the data; the others on *Gilliss* data only.

5. Conclusion

The drop size measurements in GATE support earlier indications that tropical oceanic showers differ from those in many other locations in that they tend to have a very large number of medium-sized drops ($1\text{ mm}<D<2\text{ mm}$) and relatively few large drops ($D>3$ mm). As a result, the rainfall rate and rainwater content associated with a given reflectivity value are higher than for most other places.

Empirical relations between Z and the quantities R, M and A were computed and are given in (8)–(10). These relations are appropriate for use in interpreting radar data taken during GATE, and are probably also applicable to tropical maritime showers in general. The Z-R relation, in particular, is based on drop samples from all of the platforms in the experiment and we note that every data point lies within a factor of 2 in R of the best-fit line. Somewhat different relations emerge from the individual data sets but, since the reasons for the differences cannot be determined, all the data have been given equal weight. We feel that the data are sufficiently reliable to have confidence in the results presented here, but doubt that they are comprehensive enough to warrant attempts to reduce the uncertainties through further refinements or analysis.

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