Evolution of Peaks in the Spectral Distribution of Raindrops from Warm Isolated Maritime Clouds

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ABSTRACT

Two and one-half years of observations and measurements of isolated maritime clouds in Guadeloupe (Lesser Antilles) are presented. Raindrop spectra are measured on the ground with a Joss device and an Epson PX8 Analyser. The greatest rainfall rate R is about 60 mm h^{-1}. In the raindrop spectral distributions, localized drop diameter peaks are present at 0.6, 1.0, 1.8 and 3.0 mm. These diameters are compared to those measured and calculated by other authors. The high humidity in the subcloud layer and a negligible effect of the collisional breakup mechanism make rain spectra on the ground very representative of those at the cloud base level. When the rainfall rates increase, the spectra shift towards larger diameters. Thus, different spectral distributions correspond to different values of the rainfall rate. During a given shower, spectra with small drops are first observed, followed by ones with larger drops, and small drops reappear at the end of the shower. This shift cannot be attributed to the coalescence-breakup mechanism. It corresponds to a sorting of the drops. The time evolution of these spectral distributions and the negligible effect of collisional breakup during a shower allow to propose a simplified model of single maritime clouds. Cloud thickness, water contents and the updraft speeds are related to the rainfall rates. The existence of preferred drop diameters makes the relationship simple but this result can be generalized to spectra that do not show peaks. A fit to the shape of one spectral peak is suggested with a practical application. A determination of R from the maximum values of the peaks is proposed.

1. Introduction

For many years research has been carried out on raindrop spectral distributions measured near the ground. First, the global mean shape of spectral distributions was studied in order to provide relations with radar reflectivities (Waldvogel 1974; Seliga et al. 1986). Since 1948, the Marshall–Palmer (MP) exponential distribution has been used in numerical simulations to calculate the rainfall rate. Srivastava (1971) and Willis (1984) found large deviations from the MP distribution and instead proposed a gamma-type distribution.

Low and List (1982), using numerical and laboratory work, predict privileged diameters. Valdez and Young (1985) and List et al. (1987) calculate trimodal spectral distributions. Steiner and Waldvogel (1987) observed that localized peaks are present in rain spectral distributions. Actually, since 1953, peaks have been detected at the same diameters (Mason and Rhamanadhan 1954); they also refer to Blanchard (1953). Our study emphasizes the presence of these localized peaks.

The main points of the research to be presented here are first a description of raindrop spectra. They were determined by ground based measurements performed over a period of 2½ years. The rains selected are those generated by isolated maritime cumuli. These clouds form offshore, move with the east and northeast trade winds, and reach the south coasts of Guadeloupe (Lesser Antilles). (See sampling sites in Fig. 1.) The observed showers corresponding to single clouds are short, lasting a few minutes, and their intensity is not larger than 60 mm h^{-1}.

We describe the evolution of the spectra while the cells pass over the sampling site. We consider the case of different rainfall rates. We will show that, due to the high humidity of the subcloud layer in Guadeloupe, the spectral distributions near the ground look like those measured at the base of the cloud. They contain peaks. This conclusion is supported by measurements at two altitudes.

In section 2, the methods of observation are presented. In section 3, the experimental results are described and compared to other measurements. A discussion of those results is carried out in section 4, where

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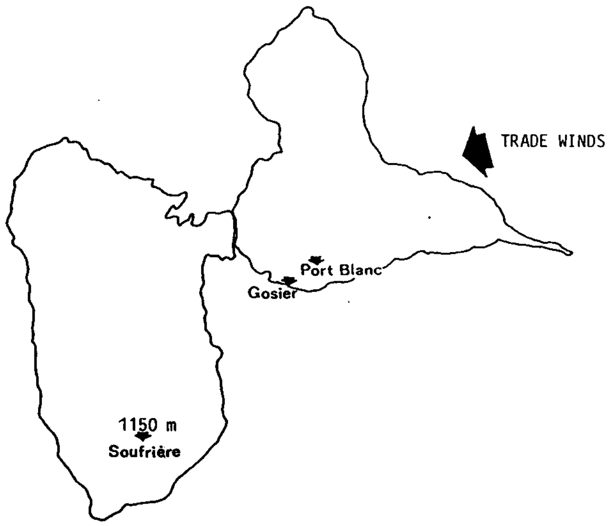


FIG. 1. Sampling sites in Guadeloupe Island.

the measured spectra are compared to spectra calculated by List et al. (1987), Valdez and Young (1985). A relatively simple relationship between the raindrop spectra and features of the clouds is proposed for different rainfall rates.

2. Methods of observation

a. Measurement conditions

Three sets of data were collected. The first measurements were made for 9 months on the flat part of the island of Guadeloupe near Gosier (see Fig. 1) with a variable recording time of 2 to 45 min. This time corresponds to the passage of a complete shower. Improvements in the experimental system allow measurements of 1-min spectra. This time of 1 min is such that the sample volume is large enough to be representative of the raindrop spectrum (Campistron et al. 1987). Thus, for the second and third sets of data, 1-min spectra have been recorded. The second set (Asselin de Beauville et al. 1986) was obtained on the Soufriere volcano (1150 m) (917 min) and the site of Port-Blanc (December 1985 and January 1986) (184 min). The third set has been collected since October 1986 on the site of Gosier (1540 min).

For this study we consider only isolated cumuli. These maritime clouds appear with regularity in the northeast or east trade winds. They can give rain when reaching the island coasts. They are typically 2–5 km in diameter. The cloud base is typically 600 m in the morning, rising to 800 m later in the day. The cloud top is determined by the inversion height which has been estimated from soundings collected by the Meteorological Office at Raizet Airport. The inversion height is generally about 2500 to 3000 m and below this layer the humidity related to the regular trade wind is high (70% to 90%). At this latitude, the 0°C level varies from 4500 to 5000 m. Above the inversion the humidity is low, about 30%. Therefore the clouds selected in this study are classified as "warm clouds." Moreover, the shape of the cloud top edge has been observed from the ground. Its convective cumulus shape differs from that of a cloud with a glaciated top. We have studied only those rain events which show a single shower peak. Their duration is about 10 min. Figure 2 shows a typical sequence of such showers. Few rains with two shower peaks, which also seemed to come from isolated clouds, have been eliminated. They constitute 5% of the rains from this kind of clouds. The selected rains last no more than 10 min and their maximum intensity R_m does not exceed 60 mm h^{-1}. During three months of the rainy season (October–December 1986), 75% of all the 44 rains from isolated clouds and with one shower peak have R_m lower than 30 mm h^{-1}.

On the other hand, we don't take into account multicellular clouds and rainfalls from fronts and the intertropical convergence zones.

The study of rains from maritime cellular clouds allows one to have identical sites and environmental conditions of the trade winds, leading to reproducibility in cloud formation and also reproducible evolution with time of the drop spectra.

b. Instrumental limits

A drop distribution meter (disdrometer) (Joss and Waldvogel 1967, 1977) associated with a microcomputer data acquisition system (Campistron et al. 1987) has been used. The collecting surface of 5×10^{-3} m^2 transforms the vertical momentum of a drop into an electronic impulse. Each individual drop is counted; the probability of having two drops at the same time on the sensor is negligible. The drop sensor is limited to about 200 drops s^{-1}. The maximum efficiency of the Epson PX8 Analyser with a RS-232C interface is 2047 drops by class for 1 min. This number has never been reached, even for high rainfall rates. Spectra may be registered during 1 min or for longer times.

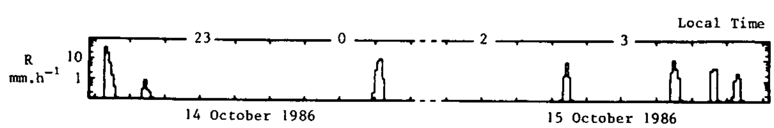


FIG. 2. Rainfall rate R (mm h^{-1}) as a function of time beginning 2145 LST 14 October 1986, and ending 0500 LST 15 October 1986.

The drops are classified according to their diameter. There are 25 diameter class intervals, each of 0.2 mm width. The first class corresponds to a central diameter of 0.4 mm. Drops from 0.3 mm to 5.2 mm can be measured, with a 5% accuracy.

In this study, 2631 1-min spectra and spectra recorded for longer times present peaks at the same locations. Steiner and Waldvogel (1987) make the existence of such peaks obvious by calculating their frequency of appearance in 1271 raindrop size distributions. They also verified that the instrument is not responsible for the multipeak behavior of the raindrop size distributions they measured, using several different electromechanical disdrometers. Like Steiner and Waldvogel (1987), we tried different calibration curves with the width of subsequent class intervals increasing as the logarithm of diameter. The peaks observed in the spectra were always at the same locations.

Since most of the 1-min spectra present either small diameters drops or large ones, the device capability of detecting drops from 0.4 to 5 mm diameter during 1 min has been checked. It is therefore possible to say that the multipeak shape of the observed spectra of this study does not have an "instrumental" origin.

3. Experimental results

a. *Description of the multipeak shape of the raindrops spectra*

In this section, we present the spectral distribution and its shape, whereas section b gives a relationship between parameters deduced from it. Then it is possible to study a complete shower as a function of time (sections c, d and e). All the variables used in this study are defined in appendix A. All the $N(D)$ spectra taken over 1 min (measured after September 1986), and spectra collected (before September 1986) for longer periods are at least bimodal. They all have spectral peaks at two or more of the following diameters: 0.6, 1.0 and 1.8 mm. For higher rainfall rates R, additional peaks appear between 2.6 and 5 mm, the most intense being at 3 mm. Typical examples of 1-min spectra are given in Fig. 3(a–f). It shows successive 1-min spectra for a shower. Some of these 1-min spectra present two peaks at 0.6 and 1 mm, others at 1 and 1.8 mm. Some of them are trimodal. By adding all the spectra of Fig. 3, the spectral distribution for a complete shower is obtained. The spectra measured in 1984 and 1985 for a whole shower have the same shape as those obtained when adding 1-min spectra of 1986.

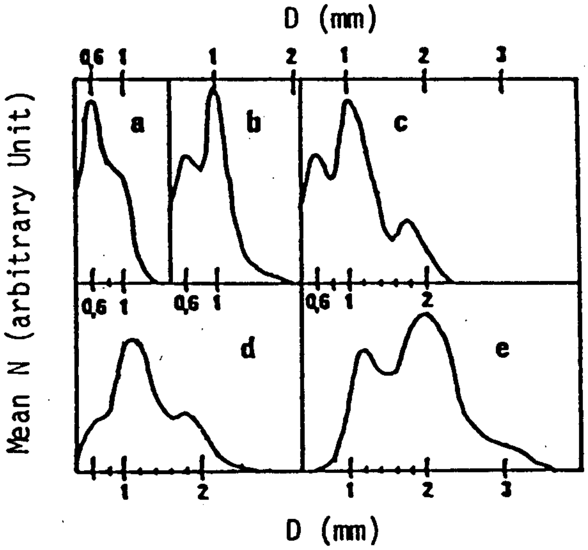


FIG. 4. Mean $N(D)$-spectra obtained from averaging 50 1-min spectra for (a) to (d), and 10 1-min spectra for (e). (a) $2 < R < 4$, all units mm h^{-1}; (b) $4 < R < 8$; (c) $8 < R < 15$; (d) $15 < R < 30$; (e) $30 < R < 40$.

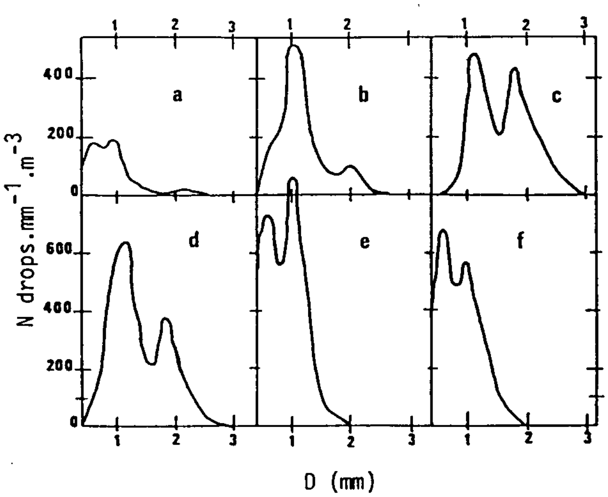
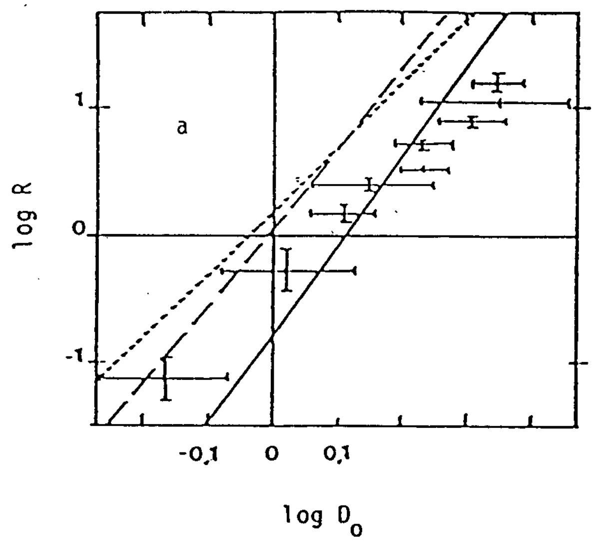


FIG. 3. Successive 1-min $N(D)$ spectra for a shower on 29 October 1986 from (a) $t = 0616$ to (f) $t = 0621$.

For a particular value of R, all the spectra have the same multipeak shape. Mean 1-min spectra (Fig. 4) had been calculated from experimental ones (from ten spectra for each R value higher than 30 mm h^{-1} and from 50 and more for the other cases). In fact, we averaged 1-min spectra from the 44 considered showers without choosing them. These mean spectra (Fig. 4) present the same peaks as those observed for 1-min spectra at the same diameters and with the same width. Thus, all the spectra considered in this section (1-min spectra of 1986, mean spectra from 1-min spectra of 1986, and spectra for complete showers measured in 1984 and 1985) present peaks at the same diameters. This and the tests made by Steiner and Waldvogel (1987), who observed such peaks, definitely confirm the existence of the peaks in the spectral distribution.

b. *The R–D_0 relationship*

An important feature of the spectra is the shift towards larger diameters for increasing rainfall rates. In



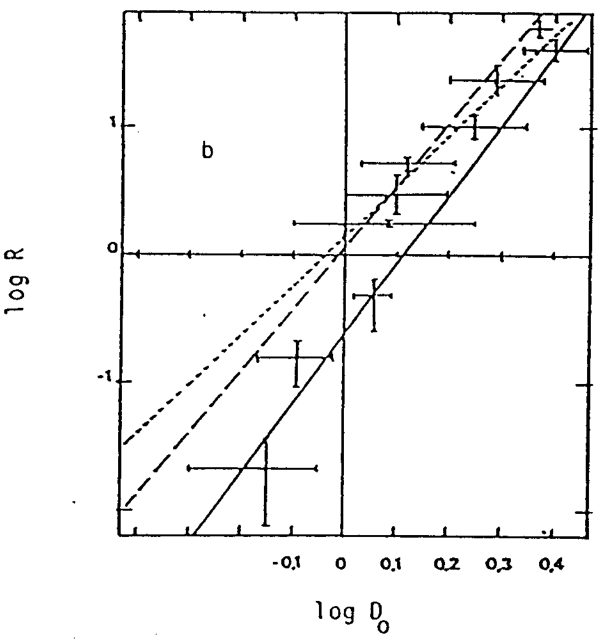


FIG. 5. A plot showing $\log R = f(\log D_0)$ decimal logarithm of R in mm h^{-1} and D_0 in millimeters: (a) from single spectra corresponding to complete showers (1984–1985); (b) from averaged 1-min spectra (1986). Theoretical curves for MP (dot), Srivastava (solid) and gamma (dashed) distributions in (a) and (b).

order to study it, a plot was prepared of the two parameters, rainrate R, and mean diameter D_0 for each spectrum (appendix A). The experimental points (Fig. 5a) are deduced from the spectral distribution corresponding to complete showers as measured in 1984 and 1985. In Fig. 5a, the experimental points have been compared to theoretical curves proposed by Marshall–Palmer (1948), Srivastava (1971), and Willis (1984) for an exponential and gamma $N(D)$ distributions respectively. Figure 5a shows a quasi-linear dependence of $\log(R)$ to $\log(D_0)$ for the experimental points.

An identical R–D_0 plot has been made from the mean spectra obtained from 1-min spectra of 1986 in Fig. 4. The dependence of $\log R$ to $\log D_0$ is still linear (Fig. 5b), at least above $D_0 = 0.6$ mm. Below this value the results are not significant, due to the experimental limit of the disdrometer. (The smaller measured diameter is 0.4 mm.) In Fig. 5b, we just observe a larger slope of the line. This can be related to the subsequent remark: For small values of R, the contribution from small drops is the only one in 1-min spectra as well as in spectra recorded during a whole shower. Thus in both cases, the R–D_0 relationship is identical. But, for higher values of R, spectra of a complete shower contain all drop diameters, while only large diameters appear in 1-min spectra. Thus, for a given large value of R, D_0 is normally larger for 1-min spectra.

c. Time dependency of R and N_G

As indicated in section 2a, this study is limited to rains with only one shower peak (Fig. 2). A typical example of the $R(t)$ dependency is given in Fig. 6. For each experimental 1-min spectrum, the total number of drops, N_G, and the intensity R, have been calculated. Figure 6 shows the values of R and N_G for different times from the beginning to the end of a given shower. The two curves $R(t)$ and $N_G(t)$ present a maximum at the same time, t_m. But the peak of N_G is broader. This comes from the fact that at the beginning and the end of the rain, there are small drops which give a negligible contribution to R while N_G may be large.

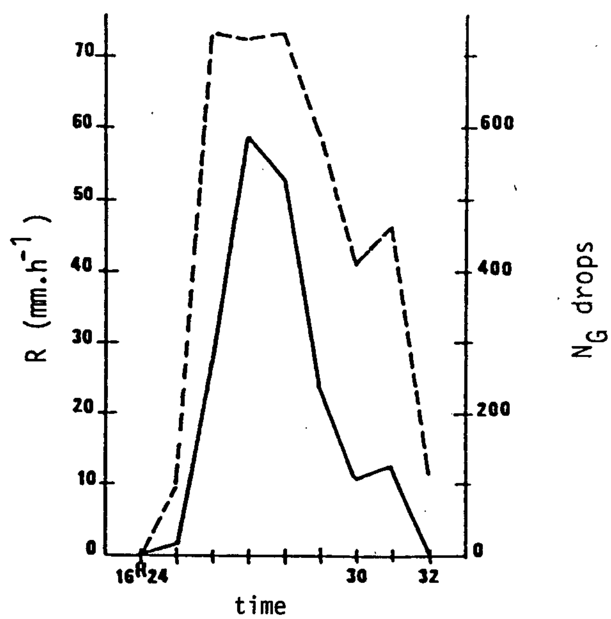


FIG. 6. $R(t)$ (solid) in millimeters per hour and $N_G(t)$ (dashed) total number of drops, for a shower from an isolated cloud on 2 November 1986. At t = 1627 LST, R_m = 58.84 mm h^{-1}, N_G = 720 drops per cubic meter per millimeter of diameter.

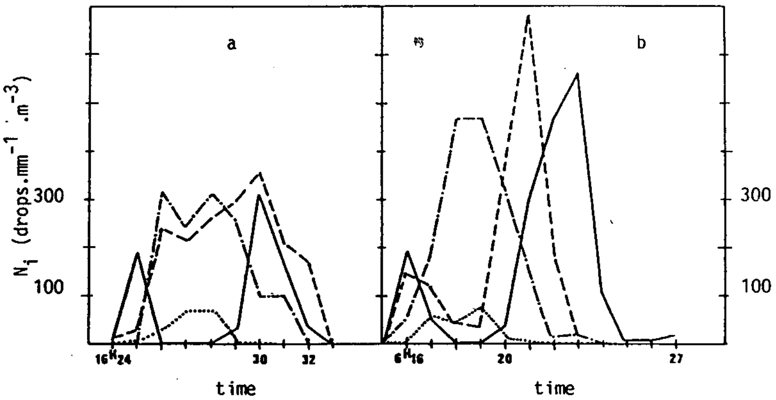


FIG. 7. Evolution with time of the maxima N_i of the following peaks: (a) 2 November 1986, R_m = 58.84 mm h^{-1} at t = 1627; (b) 14 October 1986, R_m = 60.6 mm h^{-1} at t = 0619. Legend: $N_{0.6(t)}$ (solid), $N_{1.0(t)}$ (dashed), $N_{1.8(t)}$ (dash-dot), $N_{3.0(t)}$ (dot).

d. *Time dependency of the raindrop peaks near t_m for different maximum rainfall intensities*

In this study, the successive $N(D)$ 1-min spectra differ during a given shower. This allows a study of their evolution with time.

1) $N_{0.6}(t)$, $N_{1.0}(t)$, $N_{1.8}(t)$, AND $N_{3.0}(t)$

Figure 3 shows the successive one-minute spectra corresponding to a given shower as a typical example. At the beginning of the shower, the 1-min spectrum presents two peaks of small diameter drops, at 0.6 and 1 mm. Later, when the rainfall rate increases (Fig. 6), the small diameter peaks decreases toward zero while peaks at 1.8 mm, 3 mm and larger diameters are observed. At the end of the shower, two peaks, at 0.6 and 1.0 mm, are again observed.

The time evolution of $N(D)$ spectra has been followed by studying the time dependency of the peaks at 0.6, 1.0, 1.8 and 3 mm. We observe that the width of each peak is constant with time (appendix B).

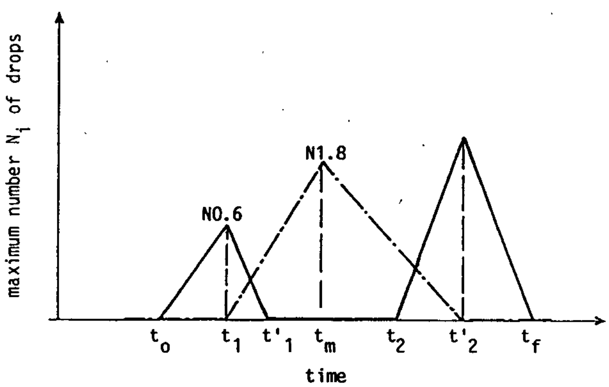


FIG. 8. Schematic time evolution of maxima of the number $N_{0.6}$ of 0.6 mm drops and the number $N_{1.8}$ of 1.8 mm drops, for R_m = 40 mm h^{-1}.

Therefore the maximum values of $N(D)$ for those peaks, $N_{0.6}$, $N_{1.0}$, $N_{1.8}$, and $N_{3.0}$ have been plotted as a function of time (Figs. 7, 8, 9) during a given shower.

2) ROLE OF THE MAXIMUM RAINFALL INTENSITY

We noted that different rains having nearly the same maximum R value have the same evolution; i.e., they last the same length of time and the time dependency of N_i for a given peak at D_i is identical. This leads us to examine separately rains of different maximum rainfall intensity R_m.

3) A LARGE MAXIMUM RAINFALL RATE, R_m = 60 MM H^{-1}

Figure 7a, b shows evolution of the peaks of $N(D)$ for two rainfalls with R_m = 60 mm h^{-1} with a duration of 9 min each. These two showers represent the only events in this study with R_m > 40 mm h^{-1} from isolated clouds. The time evolution for the two peaks at 0.6 and 1.8 mm is identical for both showers (Fig. 8). From the beginning of the shower, the number of small drops, $N_{0.6}$, begins to grow with time up to a maximum occurring at t_1. At this time, t_1, drops of diameter 1.8 mm appear and their number, $N_{1.8}$, grows, while $N_{0.6}$ decreases; $N_{0.6}$ vanishes from t'_1 to t_2, while $N_{1.8}$ goes through a maximum at t_m. From t_m, $N_{1.8}$ decreases and $N_{0.6}$ appears for a second time, reaching a maximum value at t'_2. The time t'_2 corresponds to the disappearance of 1.8 mm diameter drops. At the end of the shower, $N_{0.6}$ decreases, resulting in a slow decrease of the rain intensity toward zero. The experimental results (Fig. 7a, b) show the time dependency described on Fig. 8 for $N_{0.6}$ and $N_{1.8}$. Moreover, $N_{1.0}$ varies with time like $N_{0.6}$; i.e., the number of small drops $N_{0.6}$ and $N_{1.0}$ vanishes near t_m. For the two showers of Fig. 7a, b, a peak at 3 mm also appears; $N_{3.0}$ varies like $N_{1.8}$, being always smaller than $N_{1.8}$.

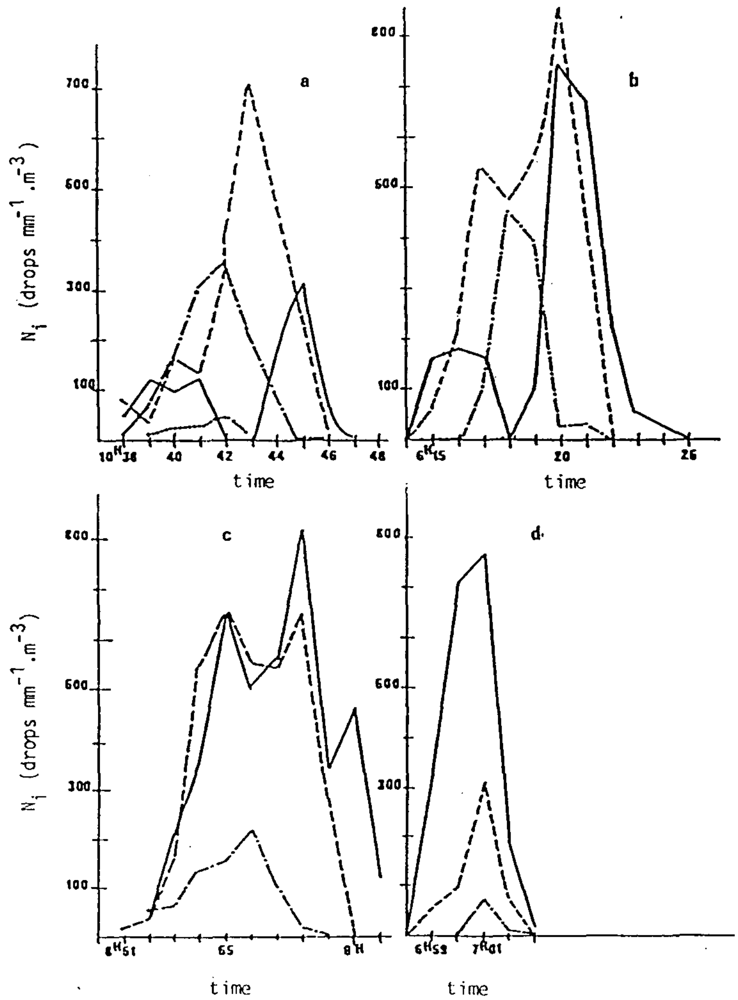


FIG. 9. $N_{0.6(t)}$ (solid), $N_{1.0(t)}$ (dashed), $N_{1.8(t)}$ (dash-dot), $N_{3.0(t)}$ (dot): (a) 14 November 1986 from 1038 to 1048 LST, R_m = 43 mm h^{-1}; (b) 29 October 1986, from 0614 to 0621 LST, R_m = 36 mm h^{-1}; (c) 27 October 1986, from 0850 to 0904 LST, R_m = 14 mm h^{-1}; (d) 27 October 1986 from 0659 to 0703 LST, R_m = 4.8 mm h^{-1}.

4) SMALLER MAXIMUM RAINFALL RATE

The time dependency for showers having lower maximum rainfall rates R_m is represented in Fig. 9a, b, c, d.

For the cases shown in Fig. 9a and 9b, the R_m values are nearly identical at 43 and 36 mm h^{-1}, respectively. These values are relatively large for one isolated cell. The duration of the two rainfalls is nearly the same: 9 minutes. The time dependencies of the peaks at 0.6 and 1.8 mm are those of Fig. 8. The evolution of the 1.0 mm diameter peak looks like the 0.6 mm one, but the 1.0 mm peak does not vanish near t_m, as the 0.6 mm peak does. At t_m, it just presents a small lowering or a dead level. Moreover, for the cases of Fig. 8a and 8b, there is a peak at 3 mm. Its time dependency is nearly the same as that of the 1.8 mm peak; however, the number $N_{3.0}$ is small compared to $N_{1.8}$.

For smaller rainfall rates (Fig. 9c, d) the time evolution is slightly different. First of all, the rain duration is a little smaller. For R_m = 14 mm h^{-1} (Fig. 9c), the spectra present peaks at 0.6, 1.0, and 1.8 mm. The opposite behavior of $N_{0.6}$ and $N_{1.8}$ with time still exists, but $N_{0.6}$ does not vanish at t_m as it is the case for higher values of R (Fig. 7, 8 and 9a, b).

In the case of Fig. 9d (R_m = 4.8 mm h^{-1}), there are very few big drops. Here, $N_{0.6}$ and $N_{1.0}$ just increase up to a maximum when R is maximum ($t = t_m$) and then decrease to zero.

e. Time dependency of the peaks near the beginning and the end of the showers

At the beginning and the end of the showers, we observe spectra with small drops. For all rains in Figs. 7 and 9, the intervals (t_1, t'_1) and (t_2, t'_2) of Fig. 8 can be considered as corresponding to the appearance and disappearance of 0.6 mm diameter drops. In all cases, those two intervals are rather small. They both last 2 min for all R_m values.

4. Discussion about the results

a. Distribution law for the ground spectra

Steiner and Waldvogel (1987) measured spectra for complete showers. They found peaks at drops diameters of 0.7, 1.0, 1.9 and 3.2 mm, slightly different from those observed in this work. We cannot eliminate specific factors which should explain the discrepancy between our observed drops size peaks and those of Steiner and Waldvogel. First, these authors did not specify whether they have considered warm clouds or not. Second, a difference may exist between the sizes near the ground, the peaks diameters being the same at the base of the cloud. Nevertheless, this shift is relatively small, taking account of the resolution of the instrument (the class interval is 0.2 mm). On another hand, the relative intensity and the width of the peaks constituting the spectra vary for each spectrum. Moreover, the width (about 0.4 mm at half height) is very near the distance between two neighboring peaks. Therefore, the error on the diameter of the maximum of one peak is at least 0.1 mm. We also note that Steiner and Waldvogel (1987) give a relationship between the probability of appearance of peaks of different sizes and the rainfall rates which is the same as that observed by us (Fig. 5). Since the accuracy of the different disdrometers have been checked, the discrepancy between our values and theirs is not attributed to the instruments. It is then possible to say that we observe the same peaks as they did.

Actually, nearly all experimental spectral distributions (Blanchard 1953; Willis 1984; Steiner and Waldvogel 1987) show localized peaks. But they are more or less concealed in a logarithmic representation of $N(D)$. The use of $\log N(D)$ instead of $N(D)$ makes a comparison with the MP distribution easier. Nevertheless, such peaks are predicted by coalescence–breakup calculations for equilibrium spectra (Low and List 1982; Valdez and Young 1985).

The presence of strong peaks made a good fit to Marshall–Palmer and gamma laws (Willis 1984) impossible. Since measurements during times smaller than 1 min should give thinner peaks than those observed, the real widths of the peaks may be smaller than the measured ones and it seems to be too early to try a perfect fit of experimental spectra with a theoretical function.

In appendix B, a gaussian distribution, a classical curve that roughly agrees with the experimental shape for a peak, has been proposed. The raindrop spectral distribution is thus completely defined by the knowledge of the diameter and width of each spectral peak.

b. R–D_0 relationship

Our experimental results (Fig. 4) are in agreement with general predictions for rain intensity: linear dependence of $\log R$ to $\log D_0$. But they do not allow us to choose a particular distribution law (Fig. 5a, b). Such a remark about the indefiniteness of the R–D_0 relationship had also been made by Seliga et al. (1986). It can be related to the mathematic definition of R and D_0 (Willis 1984), given here in appendix A, (A1), (A2). First, the influence of small diameters in the integrals of (A1) and (A2) is negligible. The Marshall–Palmer and gamma distributions may give exactly the same result. Moreover, the $N(D)$ expression appear in the same place in (A1) and (A2), so it is not surprising that different $N(D)$ (including the multipeak type distributions) give nearly the same R–D_0 theoretical dependence.

In appendix B, a method for a rapid calculation of R and D_0 for a given spectrum is proposed, based upon a gaussian shape for each peak.

c. Comparison of our measurements with calculated raindrop spectra

The existence of drop diameters peaks at the base of the cloud seems to correspond to those foreseen, measured, and parameterized by Low and List (1982). From their hypothesis, List et al. (1987) find three particular diameters, 0.268, 0.79 and 1.76 mm. Valdez and Young (1985) also calculate a spectral distribution at equilibrium loosely related to the MP distribution with three distinct peaks at 0.24, 0.87, and 2.0 mm. The experimental diameters measured in this study differ from those of Valdez and Young (1985) and of List et al. (1987), who give smaller values. Considering these three main peaks, the large discrepancy between the smallest diameters (0.268 mm for the calculated one and 0.6 mm for the observed one) is a problem, compared to the proximity of the other two peaks. It should take a long time (nearly 1 h) to grow from 0.268 mm to 0.6 mm by coalescence–breakup in the cloud. This is aggravated by the fact that such drops (of diameter 0.268 mm) correspond to parts of the cloud with lower liquid contents (1 h corresponds to 0.15 g m^{-3}). This difference should be reduced if we consider that Steiner and Waldvogel (1987) indicate that they have observed a possible peak at 0.4 mm. We could not measure such a peak. We conclude that the measured peaks of our study and those of Steiner and Waldvogel (1987), which seem to be the same, are those calculated by List et al. (1987) at equilibrium. Therefore, we use Table 1 by Steiner and Waldvogel (1987) to compare measured and calculated values in the literature. (See our Table 1.)

Another discrepancy between observed and calculated spectra is the number of peaks and the existence of peaks at higher diameters which are not predicted

TABLE 1. Comparison of measurements of raindrop spectra with model calculations (Steiner and Waldvogel 1987). Abbreviation: Doppler radar (DR); optical spectrometer (OS); aircraft observations (AO); filter paper (FP); rain drop camera (RC); disdrometer (DM).

Peak analysis of our observations	Other observations		Model calculations	
Peak (mm)	Peak (mm)	Author, measuring system	Peak (mm)	Author
	(0.4)	Steiner and Waldvogel (1987), DM	0.2	Brazier-Smith et al. (1973)
			0.2	Young (1975)
			0.24	Valdez and Young (1985)
			0.268	List et al. (1987)
			0.4	Young (1975)
0.6	0.6	du Toit (1967), DR		
	0.6	Willis (1984), OS		
	0.7	Takahashi (1978), AO		
	0.7	Steiner and Waldvogel (1987), DM	0.7	Brazier-Smith et al. (1973)
			0.79	List et al. (1987)
1.0	0.85	Ohtake (1969), FP	0.87	Valdez and Young (1985)
	1.0	Steiner and Valdvogel (1987), DM	1.0	Takahashi (1978)
	1.0	Battan (1977), DR	1.0	Young (1975)
	1.0	Cataneo and Stout (1968), RC		
	1.1	du Toit (1967), DR		
	1.5	Takahashi (1978), AO	1.5	Takahashi (1978)
			1.6	Young (1975)
			1.65	Brown (1981)
1.8	1.9	Steiner and Waldvogel (1987), DM	1.76	List et al. (1987)
	2.0	Battan (1977), DR	2.0	Valdez and Young (1985)

by any model. We measured peaks at 3 mm and above, while Steiner and Waldvogel (1987) did so at 3.2 mm. Moreover, we do not observe drop size distributions in families that are multiples of one another: $f(D, R) = R \cdot \psi(D)$, as predicted by the model of List et al. (1987). Actually, we observe a larger contribution of large diameters for large R values, while their contribution is zero for small values of R (Fig. 3). On the other hand, such distributions (List et al. 1987) should give a unique D_0 value for spectra corresponding to different R values. This conclusion disagrees with experimental results (see section 3b, and Fig. 5).

d. Drop diameters at the cloud base

In order to confirm the existence of preferred diameters, the values measured near the ground have been compared to those at the base of the cloud (appendix C).

We verify (Table 2) that changes by evaporation of the raindrop diameters at usual humidities in Guadeloupe (mean value 80%) are small. Those diameters should vary by the collisional breakup mechanism. Simultaneous measurements of raindrops spectra at sea level and 1100 m on the Soufriere volcano slopes (at the base of the orographic cloud) give the same multipeak distributions. Therefore, it indicates that the effect of the collisional breakup mechanism is probably negligible. Moreover, Tattelman and Willis (personal communication 1987) had made aircraft measurements of drop spectra in clouds. These spectra corresponding to different heights within the cloud also contain peaks. Therefore, we conclude that there are also localized peaks at the base of the clouds, with diameters and widths close to those measured at the ground.

TABLE 2. Diameters at the altitude of 1000 m of a drop of given diameter on the ground, for different humidities.

Parameter	Diameter (μ)													
Diameter on the ground	400	600	800	1000	1200	1400	1600	1800	2000	2400	2800	3200	3600	4000
Diameter at 1000 m $H = 90\%$	456	642	824	1016	1210	1409	1606	1806	2004	2404	2804	3202	3602	4002
Diameter at 1000 m $H = 80\%$	540	680	848	1032	1220	1416	1614	1812	2010	2408	2806	3204	3604	4004

e. Time evolution of the spectra

The reproducibility of the experimental results allows a complete explanation of the time evolution of the spectra for different maximum rainfall rates. Figure 3 displays the time evolution for a given shower. The first drops observed are small ones (diameters 0.6 and 1 mm). Then larger drops (diameters 1.8 and 3 mm) appear while the smaller ones vanish. At the end of the shower, the spectral evolution is a mirror image of the beginning. In subsection 4e(1) and 4e(2), two different interpretations will be discussed.

1) COLLISION, COALESCENCE–BREAKUP BETWEEN SMALL AND LARGE DROPS

Coalescence–breakup processes had been suggested as the cause for the time evolution of $N(D)$ spectra by Waldvogel (1974), Gillespie and List (1978), and Srivastava (1978). Therefore, in our case, it is tempting to say that first the small drops disappear for the benefit of the larger ones through coalescence, and the small ones reappear through the breakup process.

But this hypothesis is in contradiction with two experimental points. First, the drawing of a curve $N_S = f(N_L)$ has been tried, where N_S is the number ($N_{0.6}$ or N_1) of small drops and N_L the number ($N_{1.8}$ or N_3) of larger drops for a given shower. But no relationship between N_S and N_L has been found. Second, it can be assumed that at the beginning of the shower, there only exist small drops of 0.6 and 1 mm diameters. They should coalesce and give larger drops (of 1.8 and 3 mm diameters). A breakup of the obtained large drops should give small diameters, as is observed at the end of the shower (Fig. 3). But there is no apparent reason to get exactly the same diameters 0.6 and 1 mm which were present at the beginning.

Thus, coalescence breakup between the small (0.6 or 1 mm) and the larger (1.8 or 3 mm) drops is seemed highly unlikely.

2) INFLUENCE OF WATER CONTENTS AND UPDRAFT CURRENTS

A sorting of the drops, depending upon their diameters, has been assumed. Measurements which have been carried on in the Hawaiian clouds [A. Rigaud and C. Pontikis (France) (personal communication 1987)] have been used since we have not yet made aircrafts measurements near Guadeloupe. They show smaller liquid water contents on the edges of the clouds. This is due to entrainment. Then it is reasonable to affirm that the edge of the cloud only contains small drops. The cloud is an isolated cell moving horizontally with the trade winds. The small drops, coming from the edges of the cell, arrive first. They will also be recorded at the end of the shower, which corresponds to the last edge of the cloud. This explains the similarity of the spectra at the beginning and the end of the shower (Fig. 3).

Since the cloud is moving horizontally with the trade winds, the raindrops measured near t_m (Fig. 8), when R is maximum, come from the central part of the cloud. There, the liquid water content is large enough to allow the formation of small and large drops.

In section 4f, the disappearance of small raindrops near t_m will be related to the updraft currents in the center of the cloud. As an example, an updraft speed of 3.5 m s^{-1} has been measured by R. Lhermitte (personal communication 1987) in the center of small isolated cells in Florida. From Table 3 which gives the theoretical terminal velocities of drops of different diameters, it appears that the smaller drops cannot fall in such updraft currents. But larger ones fall with speeds smaller than the theoretical terminal velocities.

f. Relationship between the shower and the central part of the cloud for different maximum rainfall rates

A complete study of the sorting of drops can be made for showers of different maximum rainfall rate R_m. Four preferred diameters have been observed in the raindrop spectral distributions. It has been seen in Fig. 7 and 9 that their time dependence near t_m varies with R_m. It has just been shown (section 4e) that observations near t_m are related to features of the cloud center. This suggests that observations near t_m can give at least qualitative information on the cloud top height, liquid water content and updraft currents in the center of the cloud.

Takahashi (1977) and Johnson et al. (1986) have related R_m to the top height of the corresponding cell. In the center of large cells, the updrafts are supposed to be larger. In the center of a deep Hawaiian cloud, Johnson et al. (1986) measured updrafts of 7 m s^{-1}, larger than those measured in smaller cells, as indicated above (section 4e). Recent measurements of the liquid water contents in Hawaiian clouds have been carried on by A. Rigaud and C. Pontikis (personal communication 1987). They find about 0.2 g m^{-3} on the edges of the clouds and 1.0 g m^{-3} to 1.9 g m^{-3} in the center. Moreover, higher values of the liquid water contents are found in larger cells. Thus, the rainfalls of Figs. 7, 8 and 9 will be considered near t_m from this point of view.

For a given value of R_m we consider the maximum diameter of the observed drops. The size of the cor-

TABLE 3. Theoretical terminal velocity of drops for given diameters.

Parameter	Value			
Drop diameter (mm)	0.6	1.0	1.8	3.0
Theoretical terminal velocity (m s^{-1})	3.4	4.4	5.9	7.7

responding isolated cell and the liquid water contents in its center must be large enough so that it contains those drops. On the other hand, the appearance or disappearance near t_m of drop diameter peaks in the spectra give quantitative limits to the updraft velocities in the center of the cloud.

1) R_m = 60 MM H^{-1}

For this high value of R_m, the size of the cell and the liquid water content in its center must be large enough to allow formation of large diameters raindrops up to a peak at 4.2 mm.

In Fig. 7 no drops of small diameters (0.6 and 1 mm) are observed near t_m. This is in agreement with updraft currents larger than the terminal velocity of 1.0 mm diameter drops (see table 3). However, 1.8 mm diameter drops are observed near t_m. This means that the updrafts must be slower than the terminal velocity of 1.8 mm diameter drops. Thus, an estimation of the updrafts velocities v in the center of isolated cells which give a maximum rainfall rate of 60 mm h^{-1} gives 4.4 m s^{-1} < V < 5.9 m s^{-1}.

2) R_m = 40 MM H^{-1}

If we compare this case to the preceding one, the maximum raindrop diameter (last peak at 3 mm) is smaller. This agrees with the smaller size of the cloud and with smaller maximum liquid water content.

Moreover (Fig. 9a, b), near t_m, the number of drops at 0.6 mm vanishes while the number of 1 mm diameter drops merely decreases somewhat. This can be explained by updraft speeds higher than the terminal velocity of drops of 0.6 mm diameter (see Table 3) but a little smaller than the terminal velocity of 1 mm diameter drops (3.4 m s^{-1} < v < 4.4 m s^{-1}). Compared to the cases of Fig. 7a, b, this lower updraft speed appears reasonable.

3) R_m = 14 MM H^{-1}

In this case, there are no drops of 3 mm diameter. This agrees with smaller liquid water content in the center of the cell and with a lower cloud top height, compared with the preceding cases. Moreover, near t_m (Fig. 9c), a vanishing of the 0.6 mm drops is no longer observed. This means that the central updrafts are just below the theoretical terminal velocity of 0.6 mm diameter drops: v < 3.4 m s^{-1}.

4) R_m = 4.8 MM H^{-1}

Large drops are nearly nonexistent. For rains with smaller R_m (near 2 mm h^{-1}), we only observe one peak at 0.6 mm. This corresponds to thin clouds with smaller water contents. Moreover, as can be seen on Fig. 9d, the number of small drops of 0.6 mm diameter grows near t_m. This means that the updraft currents at the center of the cell are much smaller than the terminal velocity of those drops: $v \ll 3.4$ m s^{-1}.

In conclusion, the presence of well-separated peaks in the raindrop spectral distribution makes obvious the existence of a quantitative relationship between the central updrafts in the cloud and the maximum rainfall rate. This can be deduced from the time evolution of the different peaks near t_m. This relatively simple result can be extended even to drop spectra that do not show peaks; the time dependency of the number of drops for different classes of diameters gives information on updraft currents in the cloud.

g. Edge of the clouds for different R_m values

The nearly constant value of intervals (t_1, t'_1) and (t_2, t'_2) (see Fig. 8 and section 3e), i.e., the constant time of appearance and disappearance of 0.6 mm diameter drops for rains of different rainfall rates, can be explained. These intervals correspond to what happens on the edges of the cloud at the beginning and the end of the shower. In the particular case of small R_m (Fig. 9d), the two intervals form the total shower duration. In this case the total small cloud can be compared to the edges of larger clouds.

Since 0.6 mm diameter drops are the only drops observed during these intervals, it seems reasonable to consider that the edges of isolated cells of different sizes have the same water content. This is the maximum water content in small cells corresponding to small R_m values. A value of 0.2 g m^{-3} measured in the edges of cells in Hawaii should be proposed. Further, the time dependent behavior of those drops at 0.6 mm is always the same, assuming identical updrafts at the edges of cells of different sizes.

5. Conclusion and prospects

Ground raindrop size measurements in Guadeloupe appear to be particularly interesting. The subcloud layer being nearly saturated, they give a good estimate of the spectral distribution at the base of the cloud.

The main results of this study can be summarized as follows:

• Two or more sharply localized peaks are present in raindrop spectra from maritime isolated warm clouds at drop diameters of 0.6, 1.0 mm and, for larger rainfall rates, at 1.8 and 3.0 mm. These values are close to those measured by Steiner and Waldvogel (1987); they may correspond to the peaks foreseen by List et al. (1987) and Valdez and Young (1985).

• The multipeak spectral distribution evolves towards greater diameter peaks when the rainfall rate increases, the change of drops into smaller ones not being due to collisional breakup.

• The time dependence of the peak-shaped spectra has been related to a sorting of the drops of different diameters. This hypothesis and the reproducibility of the experimental results have allowed us to classify the showers. Rains of growing maximum rainfall rates (from 0.2 to 60 mm h^{-1}) are related to growing clouds, ones increasing in thickness, water contents (at least qualitatively), and updraft speed in their central part. These results may be applied to spectra of different shapes, even those not multi-peaked. Since the spectra observed at the beginning and the end of showers of different maximum rainfall rates are identical we also conclude that the edges of the different clouds of this study are nearly identical.

- Measurements in the central part of isolated cumuli in particular of the updraft speeds should therefore provide the value of the maximum rainfall rate.

Further work concerning these points can be foreseen. This study has been performed in three places in the island of Guadeloupe. The time dependence study with many 1-min spectra has essentially been made using data obtained in the flat region. On Soufriere volcano, the same peaks appear in the raindrop spectral distributions. It would be interesting to examine the orographic rains which are much more important on this island and in others of the Lesser Antilles Archipelago.

In this report, we have studied only isolated cells. However many showers in Guadeloupe come from multicelled bands of clouds, or clouds in fronts and the intertropical convergence zone. They may have greater rainrates, up to 100 mm h^{-1}, and last longer than those studied here. It will be interesting to follow their drop spectral distributions with time.

In conclusion, these relatively simple results can be applied to other rainfalls from isolated warm clouds and may open the way to future research.

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APPENDIX A

Definition of the Used Variables

D drop diameter (mm)

$N(D)$ number of drops per cubic meter and per millimeter of diameter

D_0 median volume diameter (mm); it divides the precipitation content of the distribution into two equal parts:

$$\int_0^{D_0} N(D)D^3dD = \int_{D_0}^{\infty} N(D)D^3dD \quad \text{(A1)}$$

R rainfall rate (mm h^{-1})

$$R = \alpha \int_0^{\infty} N(D)D^3dD \quad \text{(A2)}$$

α constant factor (appendix B)

R_m maximum rainfall intensity for a given rain

t_m time when $R = R_m$ for a given rain

N_G total number of drops by minute

D_i diameter of a localized peak

i 0.6, 1.0, 1.8, 3.0 mm, for the more important peaks

N_i maximum number of drops per cubic meter and per millimeter of diameter in a 1-min spectrum at D_i

V updraft current speed in the center of a cloud

APPENDIX B

Calculation of the Rainfall Rate from the Characteristics of the Peaks

A practical application of the peak-shaped $N(D)$ spectra is a simple determination of R from the maximum values of the peaks. Each peak has been assumed to have a Gaussian shape, i.e., around the peak diameter D_i corresponding to the maximum number of drops N_i,

$$N(D) = N_i \exp(-(D - D_i)^2/\delta_i^2). \quad \text{(B1)}$$

Here, $2\delta_i$ is the width of the peak at N_i/e, D_i = 0.6, 1.0, 1.8, 2.6, and 3.0 mm, and $N(D)$ is the number of drops per cubic meter and per millimeter of diameter, measured during 1 min with a captor surface of 5×10^{-3} m^2. The rain intensity R is

$$R = 6\pi\ 10^{-4} \int_0^{\infty} N(D)V(D)D^3dD \quad (\text{in mm h}^{-1}) \quad \text{(B2)}$$

where $V(D)$ is the terminal velocity for a drop of diameter D. With Gaussian-shaped peaks of width $2\delta_i$ at D_i, with $V(D) = 4.43D^{1/2}$ m s^{-1} (D in mm) it gives, to a first approximation, and considering that $\delta_i^2 \ll D_i^2$,

$$R = 0.0148 \sum N_i D_i^3 \sqrt{D_i}\delta_i \quad \text{(B3)}$$

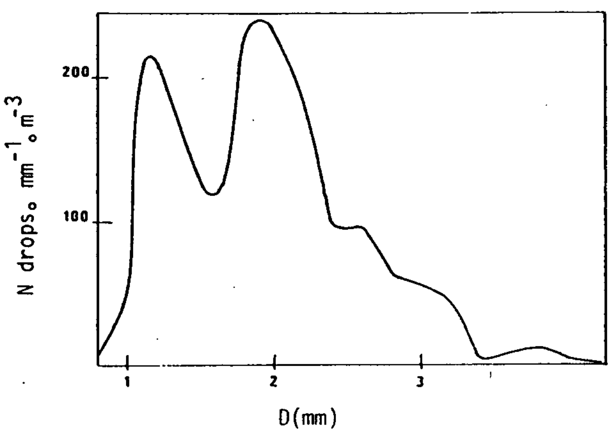

FIG. B1. One-minute $N(D)$ spectrum at 1627 LST 2 November 1986.

TABLE B1. Characteristics of the 1-min raindrop spectrum at 1627 LST 2 November 1986. (See Fig. B1)

Peak diameter D_i (mm)	Peak intensity N_i (number of drops)	Peak width δ_i (mm)
0.6	0	—
1.1	220	0.2
1.9	240	0.4
2.6	56	0.4
3.0	56	0.4
4.2	16	0.3

with D_i and δ_i in millimeters, N_i is the number of drops per cubic meter and per millimeter of diameter and R in mm h^{-1}. Equation (B3) is an underestimation of R. For many 1-min spectra of R varying from 2 to 60 mm h^{-1}, we have verified that the neglected terms are about 10% of (B3). The first neglected term in R is $0.0216 N_i \cdot D_i^{3/2} \cdot \delta_i^3$. An approximate value of D_0 can also be obtained, knowing the contribution to R of each peak. We have verified these estimations of R and D_0 on many 1-min spectra for R, varying from 2 to 60 mm h^{-1}, with good precision.

As a general example, consider the 1 min $N(D)$ spectrum of 2 November 1986 at 1627 UTC (Fig. B1). Table B1 gives the characteristic of this spectrum. Equation (B3) gives $R = 56.7$ mm h^{-1}, while $R = 58.3$ mm h^{-1} is obtained by a complete calculation which takes into account all the diameters of the spectrum from 0.4 mm to 5 mm, divided into intervals of 0.2 mm. In order to estimate D_0, the contribution of the peaks at 3 mm and 4.2 mm, 26.3 mm h^{-1} is a little smaller than $R/2$. Then $2.6 < D_0 < 3$ mm. To get more precision, the contribution of each peak i is calculated, the median diameter considered as a weighted mean is 2.65 mm. The complete calculation using all diameters D from 0.4 to 5 mm gives $D_0 = 2.62$ mm.

APPENDIX C

Drop Evaporation in the Subcloud Layer

Neglecting the curvature effects on the drop's equilibrium vapor pressure, the rate at which an individual stationary drop changes its radius a is given by Rogers (1979):

$$A = a\frac{da}{dt} = \frac{S-1}{((L_v/R_vT)-1)(L_v\rho_l/KT) + (\rho_l R_v T/D_v e_s)} \qquad \text{(C1)}$$

where

S the saturation ratio
L_v latent heat of evaporation
K thermal conductivity of air
ρ_l density of water liquid
T temperature in the environment
D_v diffusivity of water vapor
R_v specific gas constant for water vapor
e_s saturation vapor pressure.

For a drop of radius a, falling in the atmosphere, we used the mean ventilation coefficient $\bar{f}_v$ defined as the ratio of the water mass fluxes from a moving drop to that of a motionless drop (Pruppacher and Klett 1978). An approximative value of A is then

$$A = \frac{S-1}{[(L_v{}^2\rho_l)/(KR_vT^2)] + [(R_vT\rho_l)/(D_v e_s \bar{f}_v)]}. \qquad \text{(C2)}$$

In the given cases, the subcloud layer is 600 to 1000 m deep. The calculation of A has been made for an isothermal layer at 22°C, the ground temperature being nearly constant at 28°C. Here A is calculated for different drops and gives the evolution of the radius a of a drop falling at terminal velocity $u(a)$. During the time dt, the drop falls, $dh = -u(a)dt$.

Empirical formulas are used for the terminal velocity of falling drops:

$$0.1 \text{ mm} \ll a \ll 0.6 \text{ mm}, \quad u = K_1 a,$$

where

$$K_1 = 7.5 \times 10^3 \text{ s}^{-1},$$

and

$$0.6 \text{ mm} \ll a \ll 2.2 \text{ mm}, \quad u = K_2 a^{1/2},$$

where

$$K_2 = 200 \text{ m}^{1/2} \times \text{s}^{-1}.$$

In the first case

$$A = a\,da/dt = a\,da/dz(-K_1 a).$$

We integrated to find the radius a of the drop as a function of the distance h from the ground, a_0 being the radius of the drop near the ground:

$$a = (a_0{}^3 - 3Ah/K_1)^{1/3} = (a_0{}^3 - 4 \times 10^{-4}Ah)^{1/3}.$$

In the second case,

$$a = (a_0{}^{5/2} - 5Ah/2K_2)^{2/5} = (a_0{}^{5/2} - 1.25 \times 10^{-3}Ah)^{2/5}.$$

Table 2 gives the diameters at the altitude of 1000 m for different humidities (at 22°C) for given values of the radius near the ground.

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