Reply

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In their comments on our paper Willis and Merceret (hereafter W & M) take particular issue with one of our conclusions: "3) the relative absence of large drops (>2 mm) in tropical rain implies that they never grow in the first place and that the breakup process starts to reduce the growth rate of larger drops as soon as they reach sizes of 1–2 mm." It is obvious that W & M interpreted "tropical rain" as any rain in the tropics including thunderstorms which contain ice, whereas we equated it with "warm rain," i.e., rain from clouds formed by coalescence and breakup, with no involvement of the ice phase. Careful reading of our statement should make it clear that it is addressed only to the growth of drops. Hence, we feel very comfortable about their reports of drops >3 mm diameter and are pleased that the information given by Merceret (1974 a,b) is even extended and combined with data from other sources.

We would like to stress at this point that no information has been supplied by W & M which points to the occurrence of drops with diameters of 4–6 mm in warm rain or any rain in the tropics. There is indeed little difference between the spectra—as can be predicted from our model according to arguments also presented by W & M.

As to the change of drop spectra in falling rain we need to stress our modeling assumption of steady-state wide-range rain, which implies no evaporation. Thus an important factor controlling the survival chances of small drops is preset. But evaporation may easily explain some of the field measurements.

The key problem in the comparison of our first modeling results with nature is the discrepancy in speed by which an equilibrium distribution can be achieved. W & M correctly point to this problem which has been brought to our attention by Dr. J. Joss in the spring of 1976 (personal communication). In fact, the breakup in the model acts too fast. Sensitivity studies, which will be the subject of another paper, show that drops with single-peaked or double-peaked size distributions (in general non-Marshall-Palmer type) will take longer to evolve. However, we suspect that the pertinent point lies in the incomplete set of available experimental results on the drop breakup. When McTaggart-Cowan and List (1975) started their laboratory studies they did not know that relatively small drop pairs (1.8 and 0.4 mm diameter) could break up after collision. Hence they concentrated on collisions between drop pairs with diameters varying between 4.6 and 1.8 mm and 3.0 and 1.0 mm. Coalescence only occurred in a few occasions and only with the latter pair where it amounted to ~8%.

In the modeling of the spectra evolution the breakup patterns, interpolated from experiments with drops with diameters varying from 1–4.6 mm, were extrapolated to diameters of 0.5 mm. For the small drops with diameters $\leqslant 0.5$ mm [not 1 mm as erroneously stated in Eq. (21) of our previous paper] a coalescence efficiency according to Whelpdale and List (1971) was used. It is quite clear now to the authors that drops in the size range between 0.5 and 1.0 mm may control the speed of the breakup process. In particular a slow down should be achieved by the gradually increasing coalescence as the smaller drops are approaching diameters of 0.5 mm from larger sizes. The first 25 000 experiments with 5 drop pairs gave no indication about this "gray" region between 0.5 and 1.0 mm. Thus new experiment series have been started in 1974. It is hoped that extended breakup and coalescence patterns can be numerically described and made available for modeling by late 1977 or 1978. With the new information we suspect that 1) the spectra evolution will be slowed down, particularly in the cold rain case where large drops decay; 2) the equilibrium drop size distributions may contain somewhat larger drops; and 3) equilibrium distributions may often only be approached but not achieved in nature, especially for cold rain (resulting from a formation process involving the ice phase).

The simulation of the breakup and coalescence processes in the laboratory is further complicated by possible effects due to pressure. While this does not seem to be substantial it is nevertheless clear that the pressure dependence needs to be explored. Thus preparations have been taken to extend the present laboratory results to lower air densities, as they are encountered by drops in rain formation.

The authors, after studying the evolution of rain in a steady-state vertical rain shaft with sedimentation and a constant flux of rain water (Gillespie and List, 1976) also realized that special attention needs to be given to the statistical aspects of the model.

These investigations need to be followed by the inclusion of the breakup and coalescence processes into fully fledged cloud models with sophisticated dynamics. Parallel investigations on the ice phase of the cold rain will compliment these studies. The Cloud Physics Group of the University of Toronto is fully committed to such a program and has the support of the Atmospheric Environment Service, the National Research Council and the U. S. Department of Commerce through NOAA and its National Severe Storms Laboratory. Thus, an exciting development is before us and we hope that the measurements in natural rain are equally improved so that comparisons with nature are going to be meaningful indeed.

While substantial work is required, it is nevertheless clear to the authors at this point that the observed rainfall patterns clearly fit the conclusions of our 1976 paper which we could condense into the two statements: 1) sufficiently homogeneous warm rain generally consists of relatively small raindrops and 2) the occurrence of large drops in the range of 4–6 mm points to their origin from the cold rain process. Please note that relatively small drops can result from either warm or cold rain.

We acknowledge the correction by W & M about the fall distance of 3 mm drops. It is indeed about 500 m depending on pressure; 800 m is for 100 s and we realize that minutes are not yet metric units.

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