Reply

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1. Physical aspects of drop interactions

In their comments on our papers [Low and List, 1982a,b; referred to as LL(a) and LL(b)] Bradley and Stow (1984, hereafter BS) address three aspects involved in our papers, namely: the physics of the breakup process, its parameterization, and some alleged inconsistencies of the results. We will try and explain our general views and approach to the parameterization and at the same time explain why we differ with the comments expressed by these authors.

The collision of two raindrops *is not* a two-body problem; it is basically a three-body problem—the third body being represented by the air in which the collision is taking place. Thus, the centered mass frame approach, which considers just the two drops, is only creating a false feeling of security, an illusion of physical correctness. Not knowing how to approach the problem but by experiment, LL [as did ML(a) and ML(b), i.e., McTaggart-Cowan and List (1975a,b)] simulated drop collision events under conditions which duplicate nature as closely as possible. Thereby, it was recognized that even in a first-order approximation (neglecting horizontal motions) the initial momentum vector of each drop, which is acting in opposite direction to the air resistance or drag force, must act parallel to the gravity vector or weight. Thus, an adequate simulation in the laboratory of a raindrop collision process must involve the study of vertically falling drops, of drops also which are falling at terminal velocity whereby drag forces and weight are balancing each other. This was the basic assumption for the work of ML and LL, as is obvious also from their equipment design. It is not "fortuitous" as BS claim; it has been planned.

That even in vertical fall, a correct differential velocity alone is not adequate to simulate a collision between two raindrops can be easily seen by comparing ML and LL with List *et al.* (1970). In other words, "the never demonstrated effect" (see BS) had been reported some time ago. We have no specific explanation for the obvious differences, we can at this moment only suggest causes involving the substantial pressure fields around the drops, the behavior of the air between drops on collision course, different energy transfer rates with the surrounding air, the drop-internal hydrostatic pressure gradients, the vortex fields and drop-wake interactions, etc. These and other factors may need to be considered. The experimental approach chosen by ML and LL tried not to interfere with the balance of the different forces—whatever they are.

In the experiments three distinct and obvious types of breakup were observed: filaments, sheets and disks. While not every case could be specified, there was no arbitrariness in the classification. This had been demonstrated by three independent workers, the junior authors of ML, LL and List and Fung (1981), who duplicated each others results for one drop pair without any adjustments or corrections whatsoever. There is also no question about the origin of the types. Filaments result from glancing collisions where the connecting water body—while being stretched by the growing separation of the main drops—is pulled together by surface tension into a cylindrical shape, the filament. If the collision is less off-center, a rather two-dimensional sheet is formed after separation of the drops under conditions where the surface tension is no longer able to contract it into a filament in the time available. Instead, bulges at the edge and in the sheet will form the focal points for the surface tension to produce fragment drops. Disks, on the other hand, represent shapes where the smaller of the two drops will lose its identity during the collision and cannot be found again afterward.

The physical importance of the three types is also underlined by the pattern exhibited in Table 4 of LL(a), which shows that, with decreasing magnitude of the collision kinetic energy CKE, disk breakups start to disappear—they are the first to lead to coalescence—then sheets, while the breakup of the smallest colliding drops will be of the filament form. This physical aspect has led LL to subdivide the breakups into the three types even under conditions where larger numbers of events would have been desirable.

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We are aware that rotational forces have been used for physical arguments by others including Bradley and Stow (1978). We like to stress that ML have assessed them on the basis of simultaneous photographs taken at a 90° angle. Those collision point distributions are summarized in Fig. 5 of ML(b). This type of measurements was not repeated by LL because no worthwhile correlations could be established by ML. It may be that the actual rotation imparted to the large drop is much less than the photographs by Bradley and Stow (1978) suggest and that the drop separation is caused instead by the original drop inertia. Only flow visualization could establish the true effect of rotation.

Bradley and Stow comment on the "established" effect of oscillation. Fig. 11 of McTaggart-Cowen and List (1975b) measured this and, at terminal drop speeds parallel to gravity, found no effect on the outcome of collision/breakups. This is more evidence of why drop collisions with arbitrary velocity vectors are not representative of the free fall situation.

2. Interpretation of results

There seems to be confusion about some representations of the results by LL. The caption of Fig. 5 indicates clearly that C represents the number of collision experiments, i.e., all experiments. Since it was not possible to identify the type of all breakup configurations, the sum of the C_1 [LL(a)] is one short of the total of 72, whereas four breakup types C_2 could not be identified for certain by ML(b) and were therefore, left out. Figs. 11, 12 and 13 on the other hand give—again as the caption says—fragment size distributions and numbers for collision/breakup, i.e., they do not contain coalescences as Fig. 5. Coalescence frequencies can only be read directly from LL(a), Table 3. For the pair No. 6 [0.30; 0.10 cm], the overall value of the coalescence efficiency is 0.0867. We observed 7 coalescences out of 72 collisions, ML 8 out of 101. These figures can be obtained by proper manipulation of the integrated fragment size distributions in Figs. 5, 11, 12 and 13. In other words, the data sets are entirely consistent. It is also not understood where BS find 106 "lost" collisions.

We have the following additional points on the consistency of the two data sets to make: 1) As shown in Fig. 5 of LL(a), the sets are in agreement within statistical significance in almost every size bin used. 2) The main difference in the equipment from the ML setup to the one by LL was limited to a de-gassing of the water supply for the drop generators. This had a general stabilization effect at the smaller drop sizes to which LL expanded. Otherwise, equipment and measuring methodology remained unchanged [as had been mentioned before, a similar agreement had been demonstrated by List and Fung, (1981)]. The data of LL (Fig. 5) speak for themselves.

The suggestion that the aim of the smaller drop was not of a statistical scattergun type and that it was perhaps very pointed is without foundation due to the low collision success rates (<5%) in confined space. We like to recall that ML in about 25 000 attempts obtained 712 collisions, LL in about 14 000 attempts, 761 collisions. It should be further mentioned that these 39 000 attempts were only the ones—out of a more than two orders of magnitude larger body of attempts—which were flagged by an optic-electronic discrimination system as possible collisions. This time-space guess was made on the basis of the drop speeds and the drops' respective location in space. We have found no indication whatsoever that any impact point distribution on the larger drop was not flat over an area of at least three drop diameters in width and similar values in terms of equivalent distance. The ML work gave a random and even distribution of impact points within experimental significance, thus indicating no bias. In conclusion, the statements by BS of "poor statistics" and "statistically unsound" are unfounded, arbitrary and insignificant.

3. The physical basis of parameterization

Physical parameterization is meaningful if it is based on physical laws such as, for example, the Navier-Stokes equation, which leads to the establishment of the Reynolds number. Any solutions of flow patterns in two geometrically similar systems can then be scaled and are physically identical at equal similarity numbers. In the case of drop collision/breakups the governing law is the Navier-Stokes equation as applied to the two fluids involved (i.e., air and water) and extended to include surface tension. To invoke it has not produced any improved understanding of the collision/breakup process. It has therefore been tried, as is the approach by engineers, to come up with formulas containing physical quantities assumed to be important in the process. The approach may work, but the physical meaning is really lost considering the arbitrary power factors found in the relationships parameterizing the processes. We find ourselves in a very similar situation on collision/breakup parameterization [see also BS, Eq. (1)].

Furthermore, it must also be stressed that similarity theory does not allow transfer of results or comparisons between drop collision situations with arbitrary velocity vectors and simulated natural raindrop collisions in the vertical.

On this basis, we really do not see any point in discussing further the type of formulas which best describe the breakup products and is easy in terms of computation time. We are certain that simpler equations or other formulas may be found, as BS have demonstrated.

What LL have tried to achieve is to unify their results by a set of equations which allow interpolations and extrapolations within and beyond the measured range.

This parameterization gives an average fragment size distribution for two interacting drops of known diameter. If the diameter D_S of the small drop is now varied, the fragment size distribution for one given large diameter drop is then given by a continuous surface in three-space, as can be imagined on the basis of Fig. 6 in LL(b). If the diameter D_L of the large drop is also varied, then data are obtained which give the average fragment size distributions for any combination of raindrops on collision course that may be occurring in a rain shaft. This representation with both the small and the large drop diameters as variables is a surface in four-space. LL have, with their formulas, described such a surface. This leads to another comment. We should not fool ourselves by stressing and stressing only the statistical deviations of the measured points from certain cuts through this four-space surface according to very rigid and not necessarily relevant planes like D_L = constant and D_S = constant. We are dealing here not with a simple statistical problem, we are basically dealing with a topological problem because the shortest distances between measured points and the approximating surface are important in determining the accuracy. Thereby, surface peculiarities and singularities can easily play havoc with purely statistical arguments.

4. Limitations to parameterization

There is another point which is of importance and we are glad that BS have raised it. It is the question of the size of the largest fragment. Is it bigger than the larger drop originally involved in the drop pair interaction? Within the measuring accuracy of LL, no answer can be given. For the small drop, wherever a change in size can be measured, the drop will be reflected by a fragment which is smaller. This is particularly the case in the disk breakup where the identity of the small drop is lost.

Measurements of the fragment sizes are made in continuous fashion, i.e., irrespective of size classes. It is only for the averaging that the fragment drops are put into size bins and represented by histograms. These histograms are then approximated by continuous fragment distribution curves. It is obvious that, when the large fragment of a breakup can only be found in one or two bins and often within the same bin containing also the original large drop and the combined coalesced drop, the accuracy of the parameterization in characterizing the continuous measurements is quite inadequate. Furthermore, the accuracy of the present mass measurements is also too limited to answer some of the finer points which may be important in deciding if there is a limit to raindrop growth by breakup and under what conditions the growth by accretion of cloud droplets inbetween collision/breakups of raindrops could overcome a mass loss by breakup. However, before dealing experimentally with such problems, the authors would give preference to the study of effects of pressure and surface tension on collision/breakup. Further guidance from measurements of warm rain spectra and numerical warm rain modeling would also be welcome.

REFERENCES

Bradley, S. G., and C. D. Stow, 1978: Collisions between liquid drops. *Phil. Trans. Roy. Soc. London,* **A287,** 635–675.

——, and ——, 1984: Comments on "Collision, coalescence and breakup of raindrops, Parts I and II." *J. Atmos. Sci.,* **41,** 701–703.

List, R., and C. Fung, 1982: The effect of pressure on the breakup of one pair of raindrops. *Atmos.-Ocean,* **20,** 17–27.

——, C. F. MacNeil and J. D. McTaggart-Cowan, 1970: Laboratory investigations of temporary collisions of raindrops. *J. Geophys. Res.,* **75,** 7573–7580.

Low, T. B., and R. List, 1982a: Collision, coalescence and breakup of raindrops. Part I: Experimentally established coalescence efficiencies and fragment size distributions in breakup. *J. Atmos. Sci.,* **39,** 1591–1606.

——, and ——, 1982b: Collision, coalescence and breakup of raindrops. Part II: Parameterization of fragment size distributions. *J. Atmos. Sci.,* **39,** 1607–1618.

McTaggart-Cowan, J. D., and R. List, 1975a: An acceleration system for water drops. *J. Atmos. Sci.,* **32,** 1395–1400.

——, and ——, 1975b: Collision and breakup of water drops at terminal velocity. *J. Atmos. Sci.,* **32,** 1401–1411.