Laboratory Measurements of Collection Efficiencies for Accretion

HARRY T. OCHS, III AND K. V. BEARD[1]

Illinois State Water Survey, Champaign, IL 61820

(Manuscript received 18 August 1983, in final form 14 November 1983)

ABSTRACT

Collection efficiencies for accretion were measured for six pairs of nearly uncharged drops. Cloud droplets of 11 and 17 μm and collector drops between 100 and 400 μm radius were used. The resulting efficiencies were in the 51–70% range and all values were significantly below computed collision efficiencies for rigid spheres. Inferred coalescence efficiencies between 54 and 82% were found to decrease with increasing collector drop and cloud droplet sizes. Drop separation was attributed to the grazing bounce mechanism whereby an air film nullifies the relative closure velocity allowing the tangential velocity of the cloud droplet to carry it past the collector drop.

1. Introduction

The evolution of precipitation in warm clouds has been divided into two processes by Kessler (1969). The first of these is autoconversion, in which cloud water is transferred to precipitation water by the collection mechanism within the cloud water distribution. The second is accretion, in which precipitation hydrometeors collect cloud water. Berry and Reinhardt (1974) introduced a third warm rain process, self collection, which is responsible for increasing the dispersion of the precipitation water distribution. Of these three processes, the second, accretion, is the most efficient for increasing the precipitation water content. Thus a knowledge of collection efficiencies for small precipitation drops collecting cloud drops is essential for understanding warm cloud precipitation development.

There are almost no experimental data for accretion in the critical size ranges covered in this paper. Beard and Pruppacher (1971) improved on the experiments of Kinzer and Cobb (1956, 1958) for very small cloud droplets (about 5 μm mean radius) collected by 70–300 μm radius drops. Beard and Pruppacher (1971) found good ageement with the theoretical collision efficiencies of Davis (1965), Klett (1968) and Shafrir and Neiburger (1963). Neiburger *et al.* (1972) studied the accretion of 20–24 μm radius cloud droplets by 95–114 μm radius collector drops and measured collection efficiencies between 0.11 and 0.23. Abbott (1977) and also Pruppacher and Klett (1978) concluded that the efficiencies of Neiburger *et al.* (1972) were anomalously low and resulted from spurious experimental errors. Thus adequate measurements of collection efficiency are unavailable for cloud drops greater than 10 μm radius. The modeling results (e.g., Berry and Reinhardt, 1974) suggest that the mean size of the cloud droplet distribution must be at least 10 μm before significant collection can occur. In the study presented in this paper, collection efficiencies were measured in the important size regime for accretion of cloud droplets between 10 and 20 μm radius by small precipitation drops of 100–400 μm radius.

2. Experimental design and procedure

The collection efficiency was determined experimentally by measuring the amount of tracer captured by a stream of widely spaced drops falling at terminal velocity through a monodisperse cloud of chemically tagged droplets (see Fig. 1). The method was an extension of the experiment reported by Beard *et al.* (1979) and Beard and Ochs (1983). The cloud was produced by a vibrating orifice device (TSI Model 3050), whereby a liquid jet was disrupted into a stream of uniform size droplets. Recombination of droplets (e.g., doublets) was greatly reduced by dispersion in an axial jet of tubulent air and by subsequent dilution. Both the dilution and dispersion airstreams were saturated slightly above room temperature to prevent evaporation and provided saturation in the cloud chamber. The tracer solution of lithium sulfate (0.1% Li^+) was fed to the cloud droplet generator from a reservoir under pressure. An electrically neutral cloud was achieved with an ion discharge device (TSI Model 3054). The cloud was continuously generated during the experiment and flowed at 11 liters per minute through the cloud chamber (1.3 m long by 10.6 cm in diameter).

Sampling ports were located in the chamber to permit the insertion of slides coated with dye and gelatin

---

[1] Also affiliated with the Department of Atmospheric Sciences, University of Illinois, Urbana, IL 61801.

© 1984 American Meteorological Society

Unauthenticated | Downloaded 01/24/22 10:19 PM UTC

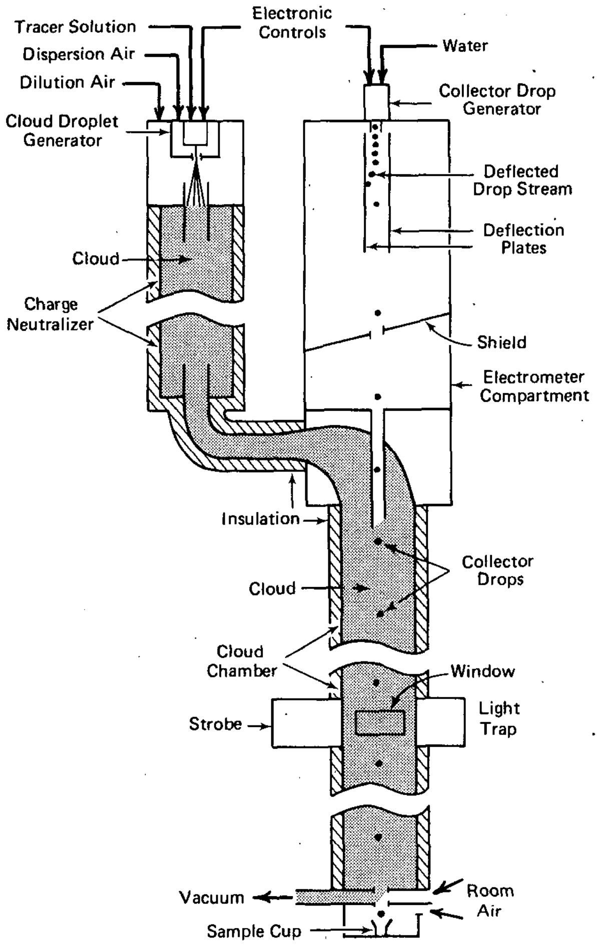

FIG. 1. Diagram of experimental apparatus.

mixture for an evaluation of the droplet sizes. The stain produced by the droplets was calibrated with an accuracy of ±0.5 μm by using the direct output of the droplet generator and was found to be consistent with the results of a similar method used by Liddell and Wootten (1957). For typical experiments, droplets in the chamber were found to be of one size (dispersion of 0.1 μm) except for an occasional doublet (<2%). The droplet concentration was measured from strobe photographs with illumination arranged in a vertical plane of well-defined thickness by two cylindrical lenses and two slits. A typical concentration for 11 μm cloud droplets was $\sim$100 cm^{-3} and $\sim$6 cm^{-3} for 17 μm droplets. The occurrence of multiple collections by a single collector drop was rare for these cloud droplet concentrations even for geometric efficiencies.

An orifice device was also used to produce the collector drops (Adam *et al.,* 1971). A pressure reservoir with a large water surface area was constructed from two 55 gallon drums so that a constant liquid flow rate could be maintained for the duration of an experiment. Drops with a wide vertical spacing (several centimeters) were separated from the main stream using a charging electrode and high voltage deflection plates. The drops reached terminal velocity within the electrometer compartment before entering the top of the cloud chamber. The vertical spacing of the drops was determined from the terminal velocity and the production rate.

During an experiment the drops were collected beneath the cloud chamber in a polypropylene jar. After chemical analysis, the collection efficiency was determined from experimental parameters using the equation

$$\mathscr{E} = M[\pi(R + r)^2 \Delta VnmXtN]^{-1}.$$

The number of collector drops (N) was calculated from the drop generation rate and the experimental time. The mass of lithium from each experiment (M) was determined by atomic absorption analysis. The collector drop radius (R) and cloud droplet radius (r) was used to obtain the relative terminal velocity (ΔV) from the equations of Beard (1976). The cloud droplet concentration (n) was determined photographically by the method discussed above. The initial droplet mass (m) was determined from the rate and generation frequency, whereas the mass fraction of lithium (X) was the initial concentration of the tracer in the cloud water solution. The interaction time (t) was determined from the fall speed of the collector drop, the downward air velocity in the cloud chamber and the cloud chamber height. Accurate knowledge of the air velocity was unnecessary because its magnitude was <2.5% of the smallest collector drop velocity. A more complete description of this equation can be found in Beard and Ochs (1983).

3. Error analysis

Chemists trained in microanalysis performed the atomic absorption measurements necessary to determine the amount of Li^+ in each sample. Chemical contamination was minimized by using disposable polypropylene jars. In addition, periodic experiments were performed without any collector drops falling through the system to check for possible contamination. The total error from chemical contamination and analysis was found to be less than 3%.

Spurious electrical forces could have altered either the collision or coalescence efficiencies. Therefore, the charge on the small cloud droplets was minimized by a charge neutralizer (Fig. 1) designed to achieve a Boltzmann charge distribution. We have computed that the mean magnitude of charge on a cloud droplet was $<2 \times 10^{-18}$ C (coulomb). The charge on the collector drop was also minimized. The measured magnitude was $<3 \times 10^{-16}$ C for the smaller collector drops and $<5 \times 10^{-15}$ C for the largest. Previously reported effects on coalescence suggests that magnitudes of $>10^{-14}$ C on oppositely charged drops are necessary to affect coalescence (e.g., Sartor and Abbott,

Unauthenticated | Downloaded 01/24/22 10:19 PM UTC

1972; Park, 1970). The force from opposite charges of this size is several orders of magnitude larger than the electrical forces in our experiment. Electric fields could have also affected the measured collection efficiencies by promoting coalescence through enhanced electrical forces. A brass experimental chamber was used to minimize electric fields. In addition, the charges and fields were too small to affect the collision efficiencies for our drop sizes (Schlamp *et al.,* 1976). Thus, we conclude that our measured collection efficiencies (collision and coalescence) were unaffected by electric forces.

A final and more subtle source of experimental error is a depletion effect. Since one collector drop follows the next through the center of the cloud column, there is a tendency for depletion of the cloud droplet concentration by the stream of collector drops. This effect would produce an anomalously low collection efficiency. Therefore, the experiments were conducted only at sufficient collector drop separations to render the depletion effect negligible. A more complete description of the error analysis can be found in Beard and Ochs (1983).

4. Results

Table 1 shows values of R, r, p, and $\mathcal{E}$ for six drop size pairs derived from 38 experiments. The stated measurement uncertainty was based on the sum of the 90% confidence intervals estimated for the mean cloud droplet concentration from counting 2000 to 13 000 drops for each group of experiments and the mean tracer mass collected per collector drop in a sequence of 4 to 8 experiments. There is an additional uncertainty (not included in the table) of about 5% from the rms combination of measurement and calibration errors. The reported collector drop size is known to ±0.1% and the cloud droplet size to ±0.5 μm. The measured collection efficiency was used with the computed collision efficiency (E) from Beard and Grover (1974) to obtain the coalescence efficiency ($\epsilon = \mathcal{E}/E$). Fig. 2 shows the measured collection efficiencies and curves based on the collision efficiencies from Beard and Grover (1974). The data show a trend of decreasing efficiency with increasing cloud droplet size which is consistent with the findings of Beard and Ochs (1983). The measured efficiencies also decrease with increasing collector drop size. It is clear that the measured collection efficiencies are significantly below the computed values. Table 1 shows that for the 326 μm collector drop and the 17 μm cloud droplet, the measured collection efficiency is only 54% of the computed collision efficiency (i.e., ϵ = 54%). The estimated uncertainty of about ±10% in both the measured and computed efficiencies is not large enough to account for this difference.

TABLE 1. Experimental results.

Drop radius (μm)			Efficiency (%)		
		Radius ratio	Measured collection	Computed collision	Inferred coalescence
R	r	p	$\mathcal{E}$	E	ϵ
113	11.0	0.097	70 ± 4	85	82 ± 4
139	17.1	0.123	65 ± 3	94	70 ± 3
213	11.2	0.053	68 ± 2	89	77 ± 2
217	17.0	0.078	61 ± 6	94	65 ± 6
326	17.0	0.052	51 ± 3	94	54 ± 3
371	11.0	0.030	63 ± 2	90	70 ± 2

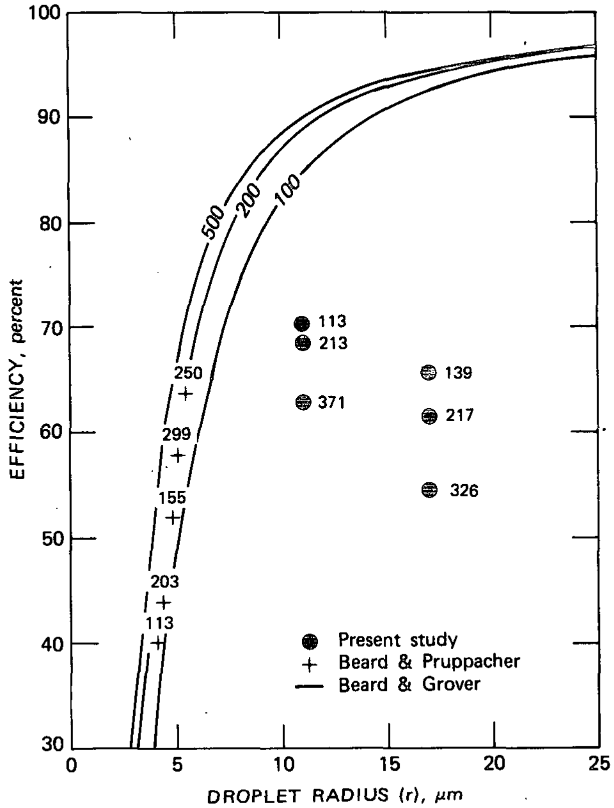

FIG. 2. Measured collection efficiencies and computed collision efficiencies as a function of droplet radius. Numerical values are the collector drop radii in microns.

Figure 2 also shows the mean collection efficiencies from the measurements of Beard and Pruppacher (1971) for collector drops in the size range of the present study. They concluded that their data agreed with theoretical collision efficiencies since the error bars overlap the computed collision efficiencies. However, the mean collection efficiencies for $R > 113$ μm are from 4 to 19% below theoretical values.

Figure 3 presents empirical coalescence efficiencies. The present data show a decreasing coalescence efficiency with increasing cloud droplet size. Thus, the higher coalescence efficiencies for 4 to 5 μm cloud droplets calculated from the data of Beard and Prup-

Unauthenticated | Downloaded 01/24/22 10:19 PM UTC

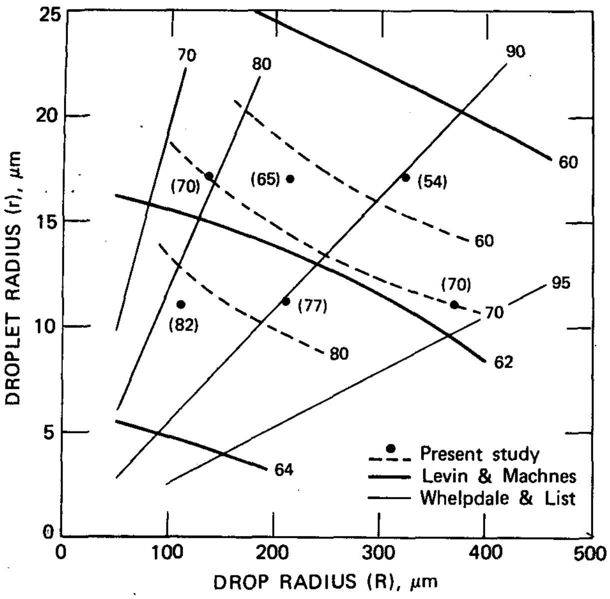

FIG. 3. Coalescence efficiencies from present data using theoretical collision efficiencies. Also shown are empirical curves from coalescence studies. The coalescence efficiency is given in percent adjacent to each data point (in parentheses) and at the end of each empirical curve.

pacher (1971) are consistent with this trend. In addition, the coalescence efficiencies also decrease with increasing collector drop size. The dashed curves in Fig. 3 are contours of constant coalescence efficiency interpolated from the present data. Fig. 3 also shows the semi-empirical coalescence efficiencies from Levin and Machnes (1977) and from Whelpdale and List (1971). Both formulations were developed from data taken outside the size ranges used in the present study and apparently cannot be extrapolated reliably to the sizes shown in Fig. 3.

5. Discussion

Beard and Ochs (1983) recognized that there were two distinct yet related physical mechanisms that can prevent coalescence for colliding drops. Both depend on drop deformation and the resulting entrapped air to reduce the closure velocity. Bouncing occurs by the *rebound mechanism* if the restoring force of surface tension causes the drops to spring apart before the air film can drain. In contrast, bouncing occurs by the *grazing bounce mechanism* if the tangential velocity of the droplet carries it past the collector drop before the air film drains. Of course, in actual drop interactions bouncing could occur as a result of some combination of these mechanisms.

Photographs of bouncing drops can help to distinguish between the rebound and grazing bounce mechanisms. Fig. 3b in Whelpdale and List (1971) shows a drop interaction where the small drop leaves the surface of the stationary large drop with a nearly tangential trajectory, an indication that bounce was due to the grazing bounce mechanism. On the other hand, Levin and Machnes (1977) show a more direct interaction in which the small drop leaves the surface with a trajectory that is far from tangential. This latter result is a clear indication of the more elastic rebound mechanism. There is also evidence to suggest that grazing bounce is primarily responsible for our coalescence efficiencies. In experiments with supported drops (Whelpdale and List, 1971; Levin and Machnes, 1977) and with streams of drops fired at each other (Park, 1970), bouncing was found to be a function of closure velocity and impact angle (measured between the vertical and the mutual center line of the drops). Extrapolation to our sizes suggests that coalescence should always be expected for direct collisions. These studies also suggest that the likelihood of bouncing increases with impact angle. A geometric interpretation of our measured collection efficiencies results in critical impact angles of >45° (i.e., for $\epsilon > 50\%$). In actuality the critical impact angle is increased and the droplet trajectory becomes more tangential because of hydrodynamic deflection. Thus we believe that the grazing bounce mechanism is primarily responsible for our results. The collector drop with its lower curvature pressure apparently indents, entraps additional air and allows the closure velocity to vanish so that the tangential velocity can carry the droplet past the collector drop.

Both the rebound and grazing bounce mechanisms depend on drop deformation to entrap air and retard contact. Foote (1975) indicates that the Weber number is the relevant parameter governing the deformation of equal size drops colliding along their line of centers. The Weber number is proportional to the ratio of an inertial force to a surface tension force and can be defined as

$$\mathrm{We} = \rho r U^2/\sigma,$$

where ρ is the density of water, r a characteristic curvature radius for the deformation, U an impact speed and σ is the surface tension. For unequal size drops there is a Weber number that characterizes each drop deformation. However, in our study we assumed that the cloud droplet was rigid and the cuvature of the deformation in the collector drop was characterized by the radius of the cloud droplet. Since the impact speed for small size ratios scales wth the collector drop velocity (V), the Weber number for our drop interactions is

$$\mathrm{We} = \rho r V^2 \sigma^{-1}.$$

When the Weber number is small, then no deformation of the collector drop occurs and the collection efficiency is equivalent to the hydrodynamic collision efficiency. Thus, as the cloud droplet or collector drop becomes smaller (r or V smaller), the coalescence efficiency should approach 100%. Conversely, the co-

Unauthenticated | Downloaded 01/24/22 10:19 PM UTC

alescence efficiency is reduced by grazing bounce as the Weber number increases in both the increasing drop and droplet size directions. The tendencies in our data (see Fig. 3) are consistent with projections based on Weber numbers.

It is interesting to compare our inference of grazing bounce to the coalescence and bounce phenomena investigated by Whelpdale and List (1971). They noted a "low velocity bounce" at the lowest impact speeds (We of 0.1–1.7) and high angles of incidence (i.e., the most grazing interactions). At somewhat higher impact speeds (We of 1.7–3.5) they found that the droplet bounced "after deformation of the drop". Apparently distortion was not seen in the low velocity case. They also found partial coalescence at still higher impact speeds (We of 3.5–7.7). The Weber numbers for our sizes ranged between 0.1 and 1.6. Thus, the interactions that we have studied are well below the impact regime for partial coalescence and within the range for low-velocity bounce.

6. Conclusions

Collection efficiencies for accretion were measured for six drop pairs. Cloud droplets from 11 to 17 μm radius and collector drops between 100 and 400 μm radius were used. The resulting efficiencies were in the 56–72% range and all values were significantly below computed collision efficiencies. Inferred coalescence efficiencies between 54 and 82% were found to decrease with increasing drop and droplet size. Poor agreement was found between our results and extrapolated values using the semi-empirical formulations of Whelpdale and List (1971) and Levin and Machnes (1977).

The mechanism of grazing bounce (Beard and Ochs, 1983) has been reasserted as the physical explanation for our coalescence efficiencies. The capture of cloud droplets by larger collector drops is important to the initiation of warm cloud precipitation and is the most important mechanism for transferring liquid water content from the cloud droplet to the precipitation distribution (Kessler, 1969; Ochs and Semonin, 1979; Johnson, 1982). Thus our findings of significantly reduced collection efficiencies should encourage the inclusion of coalescence effects in modeling studies of warm rain processes.

Acknowledgments. The authors appreciate several helpful suggestions by Roland List and the careful chemical anaysis performed by Loretta Skowron. This material is based upon work supported by the National Science Foundation under Grant ATM 8121390.

REFERENCES

Abbott, C. E., 1977: A survey of waterdrop interaction experiments. *Rev. Geophys. Space Phys.*, **15**, 363–374.

Adam, J. R., R. Cataneo and R. G. Semonin, 1971: The production of equal, and unequal size droplet pairs. *Rev. Sci. Instrum.*, **42**, 1847–1849.

Beard, K. V., 1976: Terminal velocity and shape of cloud and precipitation drops aloft. *J. Atmos. Sci.*, **33**, 851–864.

——, and H. R. Pruppacher, 1971: A wind tunnel investigation of collection kernels for small water drops in the air. *Quart. J. Roy. Meteor. Soc.*, **97**, 242–248.

——, and S. N. Grover, 1974: Numerical collision efficiencies for small raindrops colliding with micron size particles. *J. Atmos. Sci.*, **31**, 543–550.

——, and H. T. Ochs, 1983: Measured collection efficiencies for cloud drops. *J. Atmos. Sci.*, **40**, 146–153.

——, —— and T. S. Tung, 1979: A measurement of the efficiency for collection between cloud drops. *J. Atmos. Sci.*, **36**, 2479–2483.

Berry, E. X., and R. L. Reinhardt, 1974: An analysis of cloud drop growth by collection: Parts I–IV. *J. Atmos. Sci.*, **31**, 1814–1831, 2118–2135.

Davis, M. H., 1965: The effect of charges and fields on the collision of very small cloud drops. *Proc. Int. Conf. Cloud Physics,* Tokyo, Int. Assoc. Meteor. Atmos. Phys. 118–120.

Foote, G. B., 1975: The water drop rebound problem: Dynamics of collision. *J. Atmos. Sci.*, **32**, 390–402.

Johnson, D. B., 1982: The role of giant and ultragiant aerosol particles in warm rain initiation. *J. Atmos. Sci.*, **39**, 448–460.

Kessler, E., 1969: *On the Distribution and Continuity of Water Substance in Atmospheric Circulations. Meteor. Monogr.*, No. 32, Amer. Meteor. Soc., 84 pp.

Kinzer, G. D., and W. E. Cobb, 1956: Laboratory measurements of the growth and collection efficiency of rain drops. *J. Meteor.*, **13**, 295–301.

——, and ——, 1958: Laboratory measurements and analysis of the growth and collection efficiency of cloud droplets. *J. Meteor.*, **15**, 138–148.

Klett, J. D., 1968: The interaction and motion of rigid spheres falling in a viscous fluid at low Reynolds numbers. Ph.D. thesis, University of California, 113 pp.

Levin, Z., and B. Machnes, 1977: Experimental evaluation of the coalesence efficiency of colliding water drops. *Pure Appl. Geophys.*, **115**, 845–867.

Liddell, H. F., and N. W. Wootten, 1957: The detection and measurement of water droplets. *Quart. J. Roy. Meteor. Soc.*, **83**, 263–266.

Neiburger, M., Z. Levin and L. Rodriguez, Jr., 1972: Experimental determination of the collection efficiency of cloud drops. *J. Rech. Atmos.*, **6**, 391–397.

Ochs, H. T., and R. G. Semonin, 1979: Sensitivity of a cloud microphysical model to an urban environment. *J. Appl. Meteor.*, **18**, 1118–1129.

Park, R. W., 1970: Behavior of water drops colliding in humid nitrogen. Ph.D. thesis, University of Wisconsin, 577 pp.

Pruppacher, H. R., and J. D. Klett, 1978: *Microphysics of Clouds and Precipitation.* Reidel, 714 pp.

Sartor, J. D., and C. E. Abbott, 1972: Some details of coalescence and charge transfer between freely falling drops in different electrical environments. *J. Rech. Atmos.*, **6**, 479–493.

Schlamp, R. J., S. N. Grover and H. R. Pruppacher, 1976: A numerical investigation of the effects of electric charge and vertical external electric fields on the collision efficiency of cloud drops. *J. Atmos. Sci.*, **33**, 1747–1755.

Shafrir, U., and M. Neiburger, 1963: Collision efficiencies of two spheres in a viscous medium. *J. Geophys. Res.*, **68**, 4141–4147.

Whelpdale, D. M., and R. List, 1971: The coalescence process in raindrop growth. *J. Geophys. Res.*, **76**, 2836–2856.

Unauthenticated | Downloaded 01/24/22 10:19 PM UTC