A Mechanism for Giant Raindrop Formation in Warm, Shallow Convective Clouds

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ABSTRACT

Giant raindrops (4–8 mm diameter) have been observed recently within warm convective rainbands with depths ≤ 2 km off the coast of the big island of Hawaii. The presence of giant raindrops in these clouds was initially surprising since model and laboratory results support the view that collisional breakup should rapidly destroy such drops in natural clouds. A mechanism proposed by Beard et al. and others to explain the giant raindrops is that exceptionally large aerosol particles act as nuclei for very large cloud droplets near cloud base. Such rare large cloud drops then grow rapidly into giant raindrops by accretion of smaller cloud droplets in the updraft. We show here that an additional set of circumstances is required to explain the existence of giant raindrops in Hawaiian rainband clouds, one which prolongs their growth and separates them from smaller raindrops. We present data from the 1985 Joint Hawaiian Warm Rain Project that suggest that giant raindrops result when selected small raindrops recirculate from downdrafts into updrafts within eddies generated along updraft/downdraft shear zones near cloud top. We show that this recirculation mechanism is consistent with observed cloud structure both at early and late stages of cloud lifetime in Hawaiian rainbands.

1. Introduction

Raindrops with diameters exceeding 4 mm are common in thunderstorms where drops form from melting ice particles but, until recently, have not been observed in clouds whose summit temperatures are warmer than 0°C (Blanchard 1953; Blanchard and Spencer 1957; Jones 1959; Mason and Andrews 1960; Fujiiwara 1967; Carbone and Nelson 1978; Willis 1984; Bringi et al. 1984). The existence of giant raindrops (4–8 mm) in warm convective clouds was first confirmed in shallow convective rainbands off the coast of Hawaii in 1985 (Beard et al. 1986). More recently the presence of giant drops in warm convection over the southeast United States was inferred from differential reflectivity radar measurements (Illingworth 1988). These observations were quite surprising, since model and laboratory results support the view that collisional breakup rapidly destroys larger drops in natural clouds and generally limits drop diameters to a maximum of about 2.5 mm (List and Gillespie 1976; Gillespie and List 1978; Takahashi 1978; Low and List 1982). In the absence of ice, large raindrops must form by collision with other drops; however, raindrops exceeding 3 mm diameter are known from experiments to disintegrate upon collision with neighboring drops provided the neighbor's diameter exceeds 1 mm (McTaggart-Cowan and List 1975; Low and List 1982). Since millimeter-sized raindrops are generally abundant in natural clouds, the survival time of a giant drop in a field of millimeter-sized raindrops is exceedingly short (Valdez and Young 1985). How giant raindrops form and survive within these warm clouds remains an open question.

One mechanism proposed to explain giant raindrop formation is that exceptionally large aerosol particles act as nuclei for the largest droplets near cloud base, which then grow rapidly by accretion of smaller cloud droplets in the updraft (Johnson 1982; Beard et al. 1986; Caylor and Illingworth 1987; Illingworth 1988). Under very favorable conditions of high liquid water content and strong updraft velocity it has been shown that giant raindrops can indeed form from these embryonic droplets by accretion as they rise and fall through a cloud (Beard et al. 1986; Caylor and Illingworth 1987). An alternate mechanism, which we propose here, is that giant raindrops result when selected small raindrops recirculate from downdrafts into updrafts within eddies generated along updraft/downdraft shear zones near cloud top. Here we examine the ultralarge nuclei and recirculation mechanisms using data from the Joint Hawaiian Warm Rain Project (JHWRP). We show that recirculation provides a more plausible explanation for the existence of the giant raindrops, which is consistent with observed cloud structure both at early and late stages of cloud lifetime in Hawaiian rainbands.

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2. Joint Hawaiian Warm Rain Project

The 1985 JHWRP, conducted on the "Big Island" of Hawaii, demonstrated that the island provides an ideal laboratory for a broad range of meteorological studies. A large body of diverse but complementary research was initiated as a direct result of JHWRP, including studies of rain and evaporation (Takahashi et al. 1989), entrainment (Raga et al. 1990), the dynamics of island airflow (Smolarkiewicz et al. 1988; Rasmussen et al. 1988), and the evolution of droplet size spectra in orographic clouds (Baumgardner 1988). During the JHWRP we collected data to examine raindrop formation within early morning band clouds that form offshore on the windward side of the Big Island. These rainbands have summit temperatures warmer than 0°C, so ice processes do not contribute to raindrop formation. Raindrop size distributions were obtained from data collected with a Particle Measurement System 2D-P Optical Array Probe (Knollenberg 1981) mounted on the University of Wyoming King Air research aircraft. The probe was modified to have an effective photodiode size of 100 μm. This probe provided sequential drop images in strips 3.2 mm wide (Fig. 1). Drop diameters were determined using the circle fitting techniques described by Heymsfield and Parrish (1978). Because the probe was mounted with its optical axis vertical, and raindrops flatten with increasing size (Beard and Chuang 1987), the apparent diameter of images obtained with the probe (Fig. 1) is not the same diameter of the equivalent volume sphere ($d_0$). The apparent diameter is larger than $d_0$ by about 0.1, 0.3, 0.5, and 0.7 mm for $d_0 = 3, 4, 5,$ and $6$ mm. We report $d_0$ values here.

Artifact images due to droplets splashing on the probe arms were removed prior to analysis. Both accepted and rejected images were checked visually to determine if they were categorized properly by automated rejection techniques. The typical sample volume of the probe on these flights was about 0.1 m$^3$ s$^{-1}$ of flight time. Horizontal and vertical air velocity and turbulent energy dissipation rate measurements reported here were collected at 1 Hz. Vertical velocity was calculated using equations given by Lenschow (1981, 1986) using the aircraft inertial navigation system determined components of the velocity of the airstream with respect to the aircraft in the aircraft frame of reference. Eddy dissipation rate measurements were made with the Meteorology Research Incorporation (MRI) universal turbulence system (Karakostas 1981). Our conclusions are based on analysis of data obtained during 92 passes through 14 rainband clouds on 3 days.

3. Example measurements

Example measurements from a series of penetrations through a cloud on 23 July 1985, shown in Figs. 2–4, demonstrate fundamental aspects of the data. The environmental winds, measured during a takeoff sounding on the island side of the rainband, are shown on Fig. 2. In the boundary layer, offshore flow associated with island blocking and cold air drainage is evident, a typical feature observed on the windward side of the island (Smolarkiewicz et al. 1988). The trade wind layer extends to 2400 m, which was the base of the trade wind inversion and very close to the top of convective cells within the rainband. The trade wind layer shown on Fig. 2 roughly corresponds to the depth of the cloud (1.9 km), since cloud base was near 500 m. Within the layer, the wind direction was constant and variations in the horizontal wind, except at the inversion, were less than 3 m s$^{-1}$.

Figure 3 shows the raindrop size spectra for each of eight cloud passes at various altitudes. Also shown are the computed rainfall rate, radar reflectivity factor, and liquid water content averaged for each pass. The aircraft was considered to be in-cloud if any of the following criteria were met for 10 consecutive seconds: 1) droplet
concentrations measured with the Forward Scattering Spectrometer Probe were greater than 10 cm$^{-3}$; or 2) the 2DP or 2DC optical array probe concentration was greater than 1 L$^{-1}$. The optical array probes must have individually filled their buffers within 1.5 s. Figure 4 contains detailed measurements of drop size, air motion, and turbulent energy dissipation for passes D–G. The cloud was initially sampled four times at a constant altitude (1600 m). The first penetration occurred just below cloud top, with each successive penetration farther below cloud top as the cloud grew vertically. All raindrops were smaller than 3.0 mm on each of the first three passes; however, broadening of the raindrop spectra was evident (passes A–C). On the fourth pass, 3.2-, 3.8-, and 4.5-mm raindrops were found (pass D). These large raindrops were embedded within an updraft that had a peak velocity of 8.3 m s$^{-1}$, a liquid water content of 0.8 g m$^{-3}$, and a cloud drop concentration (3–48-μm diameter) of 119 cm$^{-3}$. The largest drops were isolated from the bulk of the 1–2-mm precipitation drops, which were located primarily in weak downdrafts on the flanks of the core updraft. A key characteristic of the cloud at this time was the existence of a strong shear zone (18.4 m s$^{-1}$ km$^{-1}$) between the

**Fig. 3.** Raindrop size spectra for eight passes at five elevations through a rainband cell on 23 July 1985. The total elapsed time between the first and last passes was 15 min. The star shown in pass G denotes the largest raindrop recorded, which lies off the diagram at 8.2 mm. Calculated rainfall rates, radar reflectivity factors, and measured liquid water contents averaged for each pass are also shown.

**Fig. 4.** Detailed measurements for passes D–G. Upper panels: individual raindrop sizes for all drops as a function of time from the beginning of each cloud pass. The density of the dot pattern is indicative of the drop concentration. The star shown in pass G denotes the largest raindrop observed, which lies off the diagram at 8.2 mm. Lower panels: air motion measurements; $w$ is the vertical air motion (updrafts and downdrafts), $u$ is the fluctuation from the mean horizontal air motion, and $\epsilon$ is the turbulent intensity. For convenience, turbulent intensity is plotted in units of $\epsilon^{1/3}$ (cm$^{2/3}$s$^{-1}$). (A value of 0.01 m$^2$ s$^{-3}$ is equivalent to 4.6 cm$^{2/3}$ s$^{-1}$.)
core updraft and downdraft. The largest drops resided within this zone. A strong fluctuation of the horizontal component of the wind along the direction of flight (u, see Fig. 4) was measured within the shear zone as well as the largest turbulent energy dissipation rates. The structure of the cloud on pass E at 1300 m was similar in many respects to pass D. The largest raindrops were again within the strongest updrafts, in the vicinity of the strong horizontal shear zone, and relatively removed from high concentrations of smaller raindrops. The updrafts, downdrafts, and horizontal wind shear were very weak at the lower altitude, a general characteristic of our data.

Penetrations of the cloud were made at 810, 480 (cloud base), and 140 m immediately following the passes at 1600 and 1300 m. These latter penetrations (passes F–H) were made during the mature stage of cloud development near the time when the cloud top approached the trade wind inversion at 2300 m. Giant raindrops, observed on all but the lowest pass, were found only in regions deficient of small raindrops. Key features of these and our other measurements at lower altitudes in the rainbands include the segregation of the giant raindrops into narrow regions of the cloud and the lack of substantial updraft/downdraft structure. The lack of vertical air motion at low levels later in the cloud lifetime implies that the giant raindrops were falling rapidly (∼9 m s⁻¹) from higher regions of the cloud. In order to avoid disruptive collisions, these drops must have fallen through vertical channels within the cloud in which the concentration of raindrops with diameters > 1 mm was small. We believe these channels develop in regions occupied by weakening updraft circulations. The majority of the rain, as evident from Fig. 4, falls earthward on the flanks of the former core updraft circulation. Despite the fact that these smaller raindrops possess lower terminal velocities (4–7 m s⁻¹) than giant raindrops, simple calculations show that they arrive at cloud base at nearly the same time because they primarily reside outside of the core updraft area. The largest raindrops appeared from our data to fall in the developmental stage of the rainshaft shortly after the cloud reached its mature stage.

4. Discussion

Many penetrations through rainband clouds exhibited features common to those described above. Near cloud top, larger raindrops were found either within the core updraft or the shear zone associated with the updraft/downdraft boundary. The magnitude of the shear was typically strong. The large drops were relatively isolated from the bulk of the smaller precipitation drops, which typically were located on the flanks of the core updraft. Lower in the cloud and near cloud base, the updraft structure was substantially weaker or nonexistent and downdrafts were seldom observed. When giant raindrops were observed, they were segregated into small regions of the rainshaft away from the higher concentrations of 0.1–2.5-mm drops. Our data suggest that giant raindrops appear first high in the clouds suspended in updrafts that are rich in cloud droplets but largely devoid of precipitation drops. How they arrive at this location is less clear.

A popular hypothesis forwarded to explain the initiation and rapid growth of precipitation drops in warm clouds is that exceptionally large aerosol particles act as nuclei for select cloud drops near cloud base (Johnson 1982; Beard et al. 1986; Caylor and Illingworth 1987; Illingworth 1988). These cloud drops, because of their initial large size, are thought to grow rapidly by accretion of smaller cloud droplets in the updraft and arrive near cloud top as precursor giant raindrops. The drops then fall back through the updraft to cloud base, growing by accretion into giant raindrops. Beard et al. (1986) used a continuous collection model of the kind introduced by Bowen (1950) to determine the maximum raindrop size likely to be produced by this process as a function of cloud depth and updraft velocity. In the model, use was made of realistic collection efficiencies containing reduction factors for both aerodynamic deflection and drop bounce (Beard and Ochs 1984). Figure 5 (from Beard et al.) shows the results of the model for the case of a cloud with droplet concentrations of 100 cm⁻³ and half adiabatic water content, conditions that approximate those found in Hawaiian rainbands (e.g., Raga et al. 1990). A constant updraft was assumed in time and over the entire depth of the cloud. Their calculations (Fig. 5) showed that with very strong, persistent updraft velocities over the entire cloud depth, giant raindrops can form from embryonic droplets by accretion as they rise and fall through a cloud of depth 2–3 km.

![Fig. 5. Maximum raindrop diameter predicted by a collection model (cloud base temperature 20°C, half adiabatic water content, 100 drops per cm³) as a function of cloud depth and updraft velocity (from Beard et al. 1986).](image-url)
Our data in Fig. 4 shows that such strong updrafts may indeed occur locally in the upper portion of the cloud, but are not persistent and do not extend over the cloud depth. Raga et al. (1990) have compiled statistics concerning the magnitude of updrafts in developing “main turrets” of Hawaiian rainband clouds similar to those where giant raindrops occur. A main turret was defined by Raga et al. as 1) a region of cloud that showed active growth as characterized by peak liquid water content and vertical velocity and 2) a cloud where inspection of the aircraft tracks showed that regions of active growth belonged to the same turret. Their statistics were based on penetrations of 17 rainband clouds; their results are reproduced in Fig. 6. Their analysis shows that typical updrafts averaged well less than 2 m s$^{-1}$ over the depth of actively growing clouds.

The cloud on 23 July presented here extended through a depth of 2 km. In the lower part of the cloud, during the maturing stage when the giant raindrops were falling, updrafts were weak or nonexistent. Although the lower part of the cloud during its development stage was not sampled in this case, Raga et al.’s analysis suggests that updrafts during the early stage of development of this cloud were less than 5 m s$^{-1}$. Only near cloud top did the vertical velocity exceed 5 m s$^{-1}$ and only in narrow regions of the cloud. If we apply this information to the model presented by Beard et al. (Fig. 5), we find that the maximum drop size predicted by the model for continuous growth on ultralarge aerosol would probably be less than 2 mm, and certainly less than 3 mm. Even if giant raindrops could be produced by this mechanism, they would be subjected to rapid collisional breakup, since diffusional and accretional growth across the nuclei spectrum must result in orders of magnitude more smaller raindrops in the updraft. Thus, an additional set of circumstances appears to be required to explain the existence of giant raindrops in these clouds, one which prolongs their growth and separates them from smaller raindrops.

Returning to Fig. 4, we note that the observed air motion within the zone containing the giant raindrops is characteristic of shear-induced eddy circulations. The largest scale of eddy motion from the data presented in Fig. 4, and other cases, appears to be related to the width of the shear zone, as evident in the wind fluctuations (u) for pass D. Smaller scale eddy and turbulent motions clearly exist simultaneously in the 23 July cloud. Analogous eddy circulations along cumulus cloud boundaries in two-dimensional cloud simulations indeed show similar scale selection (Klaassen and Clark 1985; Grabowski 1989). Eddy circulations between the downdraft, an environment rich in small raindrops, and the updraft, an environment rich in small cloud droplets but initially free of raindrops, should result in transport of small raindrops and cloud droplets between the primary updraft and downdraft circulations. Our calculations of turbulent transport for the measured intensity of $\epsilon \sim 0.01 \text{ m}^2 \text{s}^{-3}$ show that it is only the shear-zone scale eddies that are capable of moving the drops hundred of meters within a few minutes. This type of motion is basically a raindrop recirculation mechanism, since selected small raindrops are transported from the edge of the downdraft rather than directly into the updraft. Such a mechanism can allow select raindrops to reenter the updraft, an environment rich in cloud water that supports rapid accretional growth. Once in the updraft, these few drops can grow in the absence of disrupting smaller raindrops. Our data show that the narrow regions of the updraft in the upper part of the cloud that have sufficient velocity to suspend the larger raindrops are also associated with the strongest shear. Once drops enter the updraft core, their residence time in this rapid growth environment is increased, since they will rise with or fall slowly against the updraft.

We have constructed a simple conceptual model from our measurements (Fig. 7) that we believe characterizes the initiation, growth, and fallout of giant raindrops within Hawaiian rainbands. The model shows three stages of evolution of a cloud cell. Updrafts dominate the cloud except near the cloud top and edges in the initial stage of development (A). Near cloud boundaries, dry air entrainment and vorticity generation (Klaassen and Clark 1985) induce downdrafts that transport small raindrops downward into the cloud. Eddy circulations induced by shear instabilities along updraft/downdraft boundaries simultaneously transport selected raindrops horizontally back into the updraft. A few of these raindrops, by chance, are carried into the updraft core. Within this high liquid water content environment composed largely of cloud droplets, these selected raindrops grow rapidly, suspended
in space by the strong upward air motion. Precursor giant raindrops first appear here, high in the cloud embedded within updrafts. As the updrafts weaken (B), the giant raindrops fall to the ground through the relatively raindrop-free channel provided by the weakening updraft. Smaller raindrops falling outside the updraft channel are not suspended during their growth and consequently reach cloud base at nearly the same time. As the cloud matures (C), collision and breakup processes become dominant throughout the cloud and giant raindrops no longer develop.

Recirculation has previously been proposed as a mechanism for hail development in cold clouds (e.g., Humphreys 1940; Dye et al. 1983). Our data suggest that the production of very large precipitation particles by recirculation extends to warm clouds as well. Although this mechanism was found in Hawaiian rainbands, it need not be restricted to trade wind clouds if, as we have assumed, it is strongly tied to the nature of convection. In fact, the existence of such a recirculation mechanism in developing summertime convection in the southeast United States would explain the presence of anomalously strong polarization radar signals (Illingworth 1988). The detailed investigations planned for the Hawaiian Rainband Project near Hilo in the summer of 1990, involving aircraft and Doppler radars, will provide more extensive data for testing this and other possible mechanisms of warm rain production.

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