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WHAT IS PRODUCING SUPER-TERMINAL RAINDROPS?

G. Montero-Martínez [1], R. A. Shaw [2] and F. García-García [1]
[1]Centro de Ciencias de la Atmósfera. Universidad Nacional Autónoma de México
[2]Departament of Physics. Michigan Technological University.

1. INTRODUCTION.

A knowledge of actual raindrop fall speeds is important in rain modeling and in estimating drop size from areal detectors and for interpreting Doppler radar data (Beard, 1976; Hosking and Stow, 1991). Raindrop fall speed is also useful in fields of research such as hydrology and soil erosion. Laws (1941), Gunn and Kinzer (1949) and Beard and Pruppacher (1969), among others, have measured the terminal velocity of drops for laboratory conditions at sea level. In previous work it has been assumed that the fall speed $v_s(D)$ of a raindrop is mainly determined by its size *D* and is the same as that for water drops falling in stagnant air. In this sense, some semiempirical functions for have been developed for $v_t(D)$ of water drops (see Appendix A in Testik and Barros, 2007), although one of the most used is that from Beard (1976).

Raindrop terminal velocity v_t is the result of the balance between two opposite – gravitational and drag – forces acting on the drop during its vertical motion. During the formation and development of rain, a falling drop may interact with other cloud and precipitation particles. Gravitational effects predominate in clouds: because large raindrops have larger terminal velocities, as they fall they catch-up and collide with smaller drops in their paths (Rogers and Yau, 1989). The outcome of raindrop collision events may result in bouncing, coalescence or breakup, and the knowledge of the probability of occurrence of each of these is essential for predicting the evolution of drop size distributions (DSD).

Over the last decades, various studies have accomplished fall-speed measurements of natural raindrops with different instruments, near ground, and reported that raindrops sometimes have fall speed values different from those measured by Gunn and Kinzer (1949), which are usually used as reference for v_t (*D*). Montero et al. (2009) reported fall speed deviations of small raindrops from v_t (*D*) and purposed drop breakup as a very reasonable explanation for their observations but they did not discard other hypotheses, such as turbulence produced by air motions. The present work explores the plausibility of wind turbulence and wake effect as other probable explanations for the fall speed discrepancies of drops in the small size range.

Corresponding author's adress:
Guillermo Montero Martínez.
Universidad Nacional Autónoma de México.
Centro de Ciencias de la Atmósfera.
Circuito de la Investigación Científica. Ciudad Universitaria. Del. Coyoacán. 04510 México, D.F. México.
e-mail: gmontero@atmosfera.unam.mx

2. LARGE DROP BREAK-UP

When a large raindrop breaks up the result is the production of several fragments, all of them moving at very similar velocity than the parent one and, therefore, the smallest of the fragments moving much faster than its terminal speed. Evidence of drops in physical proximity falling faster than v_t during natural events was shown by Montero et at. (2009). From their observations, additional evidence was given to support the break-up conjecture: (i) positive skewness in the distribution of fall speed deviations, (ii) strong size dependence of fall speed deviations and their maximum values and, (iii) preponderance of super-terminal drops in the presence of large raindrops (i.e., during periods of high rainfall rates).

3. TURBULENCE

Turbulent flow is characterized by extremely irregular fluid velocity variations in time and space and it can be seen as a distribution of eddies of different size (Landau and Lifshiftz, 1987). An important parameter used to characterize turbulent flow properties is the Reynolds number *Re*, defined as the ratio of inertial forces to viscous ones. As *Re* increases, large eddies appear first and latter the smaller ones. The energy is mainly contained in the largest eddies, which extract kinetic energy from the mean field, and it is cascaded down to smaller scales through non linear interactions such as vortex stretching (Kundu and Cohen, 2004; Chuang et al., 2008). The order of magnitude of the turbulent kinetic dissipation rate ε can be estimated by those quantities that characterize large eddies (dimension and velocity fluctuation). The eddy dimension L can be estimated in function of the order of magnitude over which the fluid velocity variation Δu_L is appreciable. The order of magnitude of the energy dissipation rate in turbulent flow is given by $\varepsilon \sim (\Delta u_L)^3 / L$.

The effect of turbulent flow on the particle settling is intimately related to the interactions of particles with local structures of the flow (Wang and Maxey, 1993). The drop motion should deviate from that of the background air due to the difference in density of the two phases. An easy way to estimate this effect is by considering the frequency response of a droplet falling through an oscillating background fluid. The settling speed variation from terminal velocity for a raindrop Δu_s falling in such a system is (Chuang et al., 2008)

$$\Delta v_s = \frac{\Delta u_L}{\sqrt{1+[2\pi(\tau_s / \tau_L)]}}$$

where τ_s is the drop inertial time scale and τ_L is the residence time of a drop in any given updraft or downdraft. The inertial time is estimated by $\tau_s = 4\rho_d D / (3\rho_f C_D v_t)$, where C_D is the drag coefficient, v_t is the drop terminal speed, and ρ_d and ρ_f are the drop and fluid density, respectively. By assuming that characteristic time scale of eddies (downdraft or updraft) $L / \Delta u_L$ is larger than the time it takes for a raindrop to fall through such eddy, the residence time is calculated by $\tau_L = L / (g * \tau_d)$, where g is gravity acceleration.

From Δv_s equation, one expects that turbulent flow affects larger the small drop motion than in the case of large raindrops since the inertial (response) time of the small particles is shorter and they remain more time in the flow field.

4. WAKE CAPTURE OF THE PRECEEDING DROP

Many investigations about a sphere moving in a fluid with a constant velocity have been conducted in the past decades and document the existence of wakes behind the bodies. As the velocity of the sphere increases, two regions of essentially different types of flow become distinguishable, one in which the flow is irrotational and a second (the wake) in which the flow is predominantly rotational (Pearcey and Hill, 1956). The wake has been characterized in different flow regimes according to structure of the continuous phase behind the sphere (Magarvey and Bishop, 1961; Johnson and Patel, 1999; Gumowski et al.; Prazdka et al., 2008). Changes in the flow field produced by the wake of an hydrometeor may lead to variations of the drag force experienced by another one falling directly above during a rain event if the vertical separation is sufficiently small. In the atmosphere, the wake length is a function of the drop size (i.e., drop fall speed) and depends on the wind turbulence (Taneda, 1956; Pruppacher et al., 1970; Nakamura, 1976). According to the results of Pearcey and Hill (1956) and Steinberger et al. (1968), for pairs of droplets with similar sizes falling along their line of centers, the upper one fell faster when the vertical distance is equivalent to less than 2.5 diameters of the lower sphere and this effect increases as the separation decreases. Cataneo et al. (1971) also found a circular cone of influence downstream the leading body, whose radius is 2-3 drop diameters. On the other hand, List and Hand (1971) found, based on the detection of eddies in a cloud, that the cone of influence for 2.9 mm drops is until 5 diameters. However, they considered drop interactions must be severely affected unless the hydrometeors fall in the near wake.

5. DATA AND METHODOLOGY

Microphysical data were gathered during natural rainfall events at the Mexico City campus of the National University of Mexico during 2002, 2004 and 2006. Raindrop size and fall speed data were collected with two optical array spectrometer probes (Knollenberg, 1981) fixed on the ground and oriented vertically. Briefly, an OAP uses a photodiode array (32 active elements) and associated photodetection electronics to achieve two-dimensional information from particles passing through a laser beam at the sampling area. The drop sizing nominal ranges for the 2D-C and 2D-P devices are 0.02 to 0.8-, and 0.2 to 6.4-mm, respectively. The drop size is determined from the maximum width across the array (Figure 1). The error associated to drop size assignment is especially important as the number of elements blocked in the array decreases (the expected error for drops blocking four or less elements is above 20%) and it is the main source of error in the determination of drop fall speed.

The drop fall speed is calculated by dividing the minor axis, corresponding to the drop shape deformation (Green, 1975), by the number of slices (vertical image length in Figure 1) and the sampling frequency of the probe. Large values of sampling frequency allow one to improve the resolution for drop fall speed, depending on the calibration of the instruments, and reduce the uncertainty of the estimations. Distributions taken at high rain rate simultaneously with both instruments are mutually consistent, especially considering that the 2D-C probe, having a smaller detection cross section, measures about 50 times fewer drops than the 2D-P spectrometer, although its sampling frequency for the 2D-C is larger than that for the 2D-P. In this sense, the probe sampling frequency contributes only as a minor factor compared with the first one mentioned before.

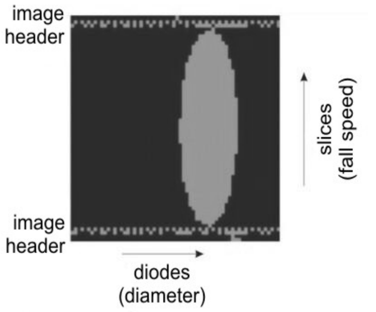

Figure 1. Two-dimensional images form as drops fall past a linear diode array, so that horizontal dimension gives drop diameter and vertical dimension gives drop speed. Detection events are separated by horizontal bar codes – the image header.

In order to rule out artifacts due to drop splashing on instruments the data presented here were restricted to calm conditions, i.e., horizontal wind speed bounded by 2 m s^{-1} and variation u'_{rms} < 0.6 m s^{-1}. Temperatures recorded during the field observations ranged from 15 to 25° C and ambient pressure was around 780 mb.

6. RESULTS.

In order to detail the differences of drop fall speed from terminal velocity based on Beard (1976), a useful parameter is the ratio between the actual drop fall speed and its correspondent terminal velocity v_s/v_t. Figure 2 shows the fall speed normalized probability distributions for the v_s/v_t ratio of drops with D ≈ 220-, 440- and 640-μm during light and heavy rain obtained from the data probes used in this study. The three panels show that the amount of drops falling at terminal speed decreases as the rain rate of the event increases. The 220 μm panel (figure 2a) displays only measurements of three bins of the 2D-C corresponding to the same range of the first one of the 2D-P. From this panel, it can be observed that the amount of super-terminal drops (those ones falling at speed values larger than v_t) can be up to 80% during heavy rain periods. For the case of 440 μm drops (figure 2b), and because both probes have the capacity to measure these drops with good precision, it is possible to make comparisons of the fall speed results obtained. Data from both probes show the same tendency for a reduction in the number of terminal drops as the rain rate increases until an amount ~50% for the cases of extreme precipitation. The histograms in the figure reveal the uncertainty differences between both probes. Since the 2D-C uncertainty is less than 2D-P, the frequency of detected drops by the first probe with fall speed different than v_t seems to be different than in the latter case. However, if the amount of 2D-C detected drops is added by considering the other probe uncertainty, then the percentages are similar (59.5% for the 2D-P and 63.4% for 2D-C).

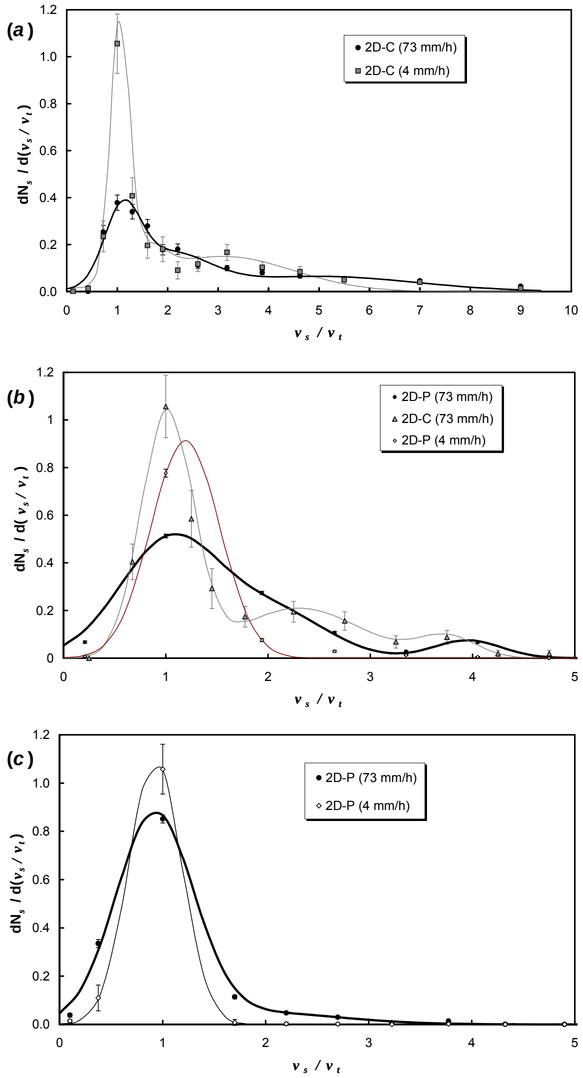

Figure 2. Drop fall-speed probability distributions for three different size ranges in function of the 2D-P resolution. Data from 2D-C were grouped from three bins to be congruent with the 2D-P diameter size range.

On the other hand, the 660 μm drops panel (figure 2c) shows that, although most of the drops of this size fall with speed values similar to theoretical (terminal) velocity, the number of drops falling slower than v_t (sub-terminal drops) increases as the rainfall intensity does the same. This result was unexpected but it puts another perspective about the fall speed of the drops with larger size diameters.

Figure 3 shows an example of a cluster of three drops (*D* = 360-, 125- and 96-μm) all of them falling faster (v_f = 709, 379 and 267 cm s^{-1}, respectively) than theoretical prediction. Note that the fall speed decreases as the drop size increases, consistent with faster relaxation to terminal velocity for smaller drops and with the fragmentation hypothesis.

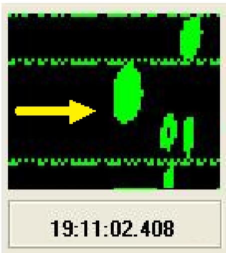

Figure 3. Super-terminal break-up fragments detected by the 2D-C probe. A two-dimensional image forms as drops fall past a linear diode array, so the horizontal dimension gives drop diameter and vertical dimension gives drop speed. See Montero et al. (2009) for more details.

Estimations of the wind turbulence effect on the drop fall speed for small raindrops during the sampling conditions reported in this work are shown in Table 1. These results confirm the expectations about the larger effect of turbulence on the smaller drops.

D	(μm)	241	438	635
$v_t(D)$	(cm s^{-1})	94	188	277
Δv_s	(cm s^{-1})	46 (49%)	23 (12%)	12 (4%)

Table 1. Estimations of the settling speed variation (Δv_s) for drops with diameter size corresponding to the first three bins of the 2D-P in accordance with the sampling conditions reported in this work. Numbers in the parenthesis refer to the variation of Δv_s respect to v_t.

7. DISCUSSION.

According to Δu_s results (Table 1), the settling speed variations are not enough to be notice in the observations: *The instrumental error (uncertainty due to sampling methodology) is larger than the expected fluctuations on drop fall speed* (except for the case of drops with *D* ≈ 220 μm). In this sense, the fluid turbulence does not seem a good plausible explanation for the observation of super-terminal drops in the measurements with the sampling conditions used in this study.

Another suggested hypothesis is about the effect produce by the wake capture of a drop by the preceding one. The design of the instruments used in the present work do not allow us to distinguish between cases of two drops are falling one above other or not (Figure 4). However, it is possible to do some theoretical estimations based on the previous work above mentioned and the characteristics of the devices used.

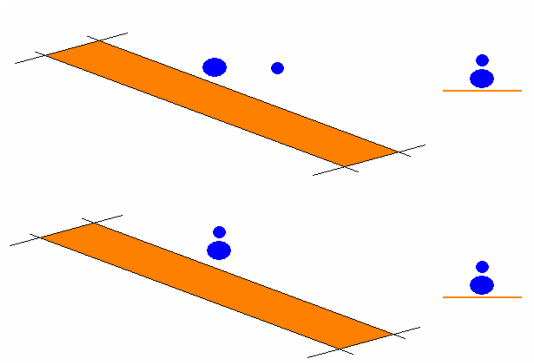

Figure 4. Possible scenarios of drops falling through the OAP sampling area (left) and their reconstructed images recorded by the measuring system (right). The probability of a drop falling above other depends on the size of the drop in the bottom and it is defined as the ratio of the cross section of a drop (A_e) respect to the sampling area of the 2D-P instrument (A_m) used during the measurements.

The wake capture effect occurs when a raindrop is falling right above other one and the distance between them is equivalent to just a few diameters of the bottom drop (bottom panel of the figure 4). So, it has been mentioned that for this case the drag force exerted upon the upper drop is smaller than when it is falling isolated producing an increment in its fall speed. The probability for a drop falling in the volume of influence of the preceding one is related to the size of the bottom drop and the (vertical) distance between them. The cross section (size) of the preceding drop is a key parameter to estimate the probability as it can be seen in the Table 2. By taking as reference the sampling area of the 2D-P, the larger the drop the larger the probability for a subsequent drop be falling in the volume drawn by the cross section of the drop in the bottom.

D (μm)	440	830	1020	1400	1970	2500	3020
Prob (%)	0.22	0.8	1.81	2.46	5.2	9.1	15.5

Table 2. Probability that a drop falls into the catchment area of the preceding drop defined as the ratio of the cross section of a drop (A_e) respect to the sampling area of the 2D-P instrument (A_m) used during the measurements in Mexico City.

Figure 5 shows the amount (percentage) of super-terminal drops which are candidates to be affected by the wake of the preceding drop. These estimations were performed with the number of super-terminal drops which were detected with an equivalent distance less than three diameters of the bottom drop and the probability results of the Table 2. *According to* Figure 5, *only a fraction of super-terminal drops with diameter sizes of 240- and 440-μm may have their origin by wake effect*. Data from this last figure do not take in account the size of the preceding drop which in most of the cases (75% for 440 μm drops) is the same or less than the super-terminal drop.

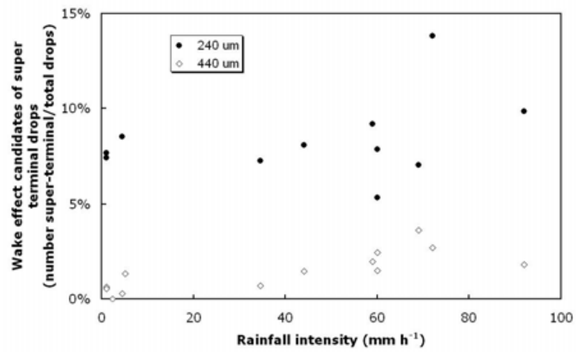

Figure 5. Estimations of the number of super-terminal drops falling in the wake (drawn volume) of the preceding drop in function of the vertical separation distance between drops and the horizontal cross section of the bottom drop.

8. CONCLUDING REMARKS.

Measurements of drop fall-speed were performed during natural rain events in Mexico City. Data were obtained from two OAPs fixed at the ground and vertically oriented. A careful analysis of the data shows that a large number of raindrops with diameter size less than 500 μm falls with fall speed values larger than those predicted from laboratory measurements and theoretical calculations. Three plausible explanations for the observation of these super-terminal drops were studied: break up of large drops, fluid turbulence, and wake effect from the preceding drop.

As expected, flow turbulence produce larger deviations in fall speed as drop size decreases. However, for the sampling conditions used for this study (horizontal wind speed less than 2 m s^{-1}), the velocity fluctuation produced by air flow turbulence is similar or less than the instrumental uncertainty, except in case of drops with diameter of 220 μm. Given the large deviations (several times v_t) observed, air turbulence does not seem a reasonable hypothesis to explain the data shown in this work.

On the other hand, probability calculations were performed by considering the limitations in the design of OAP probes. Besides these estimations, detection times were used to estimate the vertical separation distance between consecutive raindrops and to get an idea of the number of super-terminal drops which may be affected by the wake of their preceding drops. According to the obtained results, only a fraction of super-terminal drops might be the product of the wake effect. However, this fraction would be reduced if it is considered the size of the preceding drops and the results from Steinberger et al. (1968). In spite of this, measurements with other instruments such as optical or video disdrometers should give a better estimation for this particular effect.

The fast-moving raindrop cluster images and statistical significance of the velocity distribution data provide a strong evidence to support the break-up conjecture as a very (the most) reasonable explanation for the observation of super-terminal drops. Even these measurements were performed at ground level, the altitude of the sampling site (2250 masl) and environmental conditions would be similar to other places where the cloud and rain processes occur above surface, so the importance of super-terminal drops should be studied more carefully since all contributing factors (flow turbulence, wake effect and drop break-up) should take place in such environments.

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