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Key Points:
- Superterminal drops are real
- Superterminal drops are not the result of instrument splashing
- A large fraction of drops less than 1 mm in diameter appears to be superterminal

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Further evidence for superterminal raindrops

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Abstract A network of optical disdrometers (including laser precipitation monitors and a two-dimensional video disdrometer) was utilized to determine whether the recent reports of "superterminal" raindrops were spurious results of drop breakup occurring on instrumentation. Results unequivocally show that superterminal raindrops at small (less than 1 mm) sizes are ubiquitous, are measurable over an extended area, and appear in every rain event investigated. No evidence was found to suggest that superterminal drops are the result of drop breakup due to impact with the measurement instrument; thus, if the superterminal drops are the result of drop fragmentation, this fragmentation happens in the ambient atmosphere during all rain events measured in this study. The ubiquity of superterminal drops at small drop sizes raises natural questions regarding rain accumulation estimations, estimates of drop size distributions, and erosion characterization.

1. Introduction

Not all raindrops fall at the same speed; bigger raindrops have larger terminal velocities than smaller raindrops. The most commonly used relationship between droplet size and terminal fall speed was given by *Gunn and Kinzer* [1949], and though adjustments have been subsequently made for a variety of meteorological conditions, the use of the same (or similar) parameterizations for raindrop fall speeds is ubiquitous.

A recent study [*Montero-Martinez et al.*, 2009] revealed that small raindrops often fall at speeds faster than the terminal velocity of liquid drops in still air. This discovery has rapidly been noted and referenced in subsequent work [e.g., *Niu et al.*, 2010; *Villermaux and Eloi*, 2011; *Thurai et al.*, 2013]. The explanation given in *Montero-Martinez et al.* [2009] asserts that these "superterminal" drops are likely the result of the breakup of larger, faster-moving drops that generate fragments that initially continue to fall at the speed of the larger, "parent" drop. These fragments presumably slow down in time, but if the breakup occurred shortly before detection, the fragments can still be moving faster than their terminal speed.

The presence of these superterminal drops is potentially problematic particularly for those using impact disdrometers to infer drop size distributions and subsequent relationships among integrated parameters. For such purposes, the drop fluxes must be transformed into estimates of drop concentrations which are done by assuming that drops fall at their terminal velocities [*Joss and Waldvogel*, 1967]. These transformations then yield drop size distributions which can be integrated to estimate other parameters such as the radar reflectivity factor (Z). This is the basis of essentially all reported relationships in the literature between rainfall rate and Z [e.g., *Laws and Parsons*, 1943; *Marshall et al.*, 1947]. Moreover, determining the impact of natural rainfall on erosion depends on knowing reliably the kinetic energy associated with the drops, obviously affected if they are moving at superterminal speeds. Although the importance of superterminal drops on the identification of physically relevant quantities has been questioned [e.g., *Leijnse and Uijlenhoet*, 2010], it seems prudent to gather more information about the ubiquity and properties of these drops before entirely dismissing them as irrelevant to the study of rain microphysics.

To understand the impact that superterminal drops may have on rain accumulation estimation algorithms, drop size distribution estimation, or erosional estimates, it is necessary to estimate how many natural raindrops are truly superterminal. An interesting theoretical approach is provided by *Villermaux and Eloi* [2011], but more observational data are needed before the phenomenon can be widely accepted.

As noted in the study by *Montero-Martinez et al.* [2009], previous measurements of superterminal fall speeds were attributed to a variety of instrumental effects including "splashing" [e.g., *Donnadieu*, 1980;

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Table 1. Rain Events Studied[a]

Event Identifier	Start Date/Time (UTC)	Stop Time (UTC)	Total Detected Drops
Event 1	23 Dec 2013 6:20	17:04[c]	4785372
Event 2[b]	26 Feb 2014 12:40	17:12	3933823
Event 3	25 Mar 2014 4:23	23:39	4039860
Event 4	6 Apr 2014 3:00	23:58	1275651
Event 5	7 Apr 2014 21:09	22:44[c]	6945446
Event 6	15 Apr 2014 5:43	23:57	2808836

[a]Events were chosen from events in which all or nearly all instruments in the array were running properly and at least 1 million total drops were observed. Start and stop times based on first and last raindrops measured of the event by the 2DVD; most events slowly dissipated over time. All events were taken from sustained stratiform winter rain events.
[b]One of the 21 LPMs was nonoperational for event 2.
[c]Event ended the day after it began.

Hauser et al., 1984; *Hosking and Stow*, 1991; *Kruger and Krajewski*, 2002]. The *Montero-Martinez et al.* [2009] study used two optical array spectrometer probes to identify the superterminal behavior. That study ruled out splashing effects by restraining their study to calm conditions.

One might still argue, however, that fragments created during impact with the instrument may obtain new velocities that redirect the fragments into the sampling volume, no matter what the ambient wind effects may have been. There is a long history in the airborne ice detection community of trying to account for the effects of ice particles shattering on detectors like those used in the *Montero-Martinez et al.* [2009] study [e.g., *Gardiner and Hallett*, 1985; *Field et al.*, 2006; *Korolev et al.*, 2013]. One could argue that the analogue of shattering for rain detection would be a type of splashing and suggests that perhaps the measured superterminal drops might still be the result of an instrumental artifact.

Below, data are presented which (i) confirm that there is evidence for superterminal drops at small drop sizes with two new instruments and which (ii) clearly demonstrate that superterminal drops are *not* a result of a splashing on the detector.

2. Data and Methods

An array of 21 Laser Precipitation Monitors (hereafter LPM, made by Thies Clima and characterized in *Frasson et al.* [2011]) and a two-dimensional video disdrometer (hereafter 2DVD, made by Joanneum and characterized in *Schönhuber et al.* [2008] and *Kruger and Krajewski* [2002]) has been constructed and continuously acquired data since late December 2013. The array site is located at 32°44′26′′N, 80°10′36′′W. The 22 detectors are constructed in a dense array with all instruments taking data within 125 m of each other. The disdrometers are spaced logarithmically along three arms extending from a common origin out to 100 m along two of the arms and out to 52 m on one. Two of the arms are orthogonal with the third central arm bisecting the right angle. In addition, there is a 2DVD placed near the origin.

The LPM and 2DVD both detect particles through optical occlusion of a light source and infer drop velocity through a transit time measurement. The similarities between the two devices largely end there, however. The 2DVD uses two parallel white light sheets and line scan cameras while the LPMs use a single IR laser sheet; the sensing area/geometry, data output format, and physical form factor are very different for these instruments.

The LPM sorts each raindrop into one of 22 different nonoverlapping size bins ranging from 0.125 mm to 8+ mm (nonuniformly distributed) and 20 different nonoverlapping fall velocity bins ranging from 0 m/s to 10+ m/s (also nonuniformly distributed). Each minute, summary telegrams for each of the 21 LPM detectors are transmitted to an acquisition computer and are stored for use in later analyses.

The 2DVD records each raindrop's arrival time (to ms precision), fall velocity (to 0.01 ms precision, though any drops falling at less than 0.5 m/s are discarded), drop arrival location within the sensing volume (to submillimeter precision), and diameter (to 0.01 mm precision). Additionally, the associated software is able to infer approximate horizontal drop velocity during detection.

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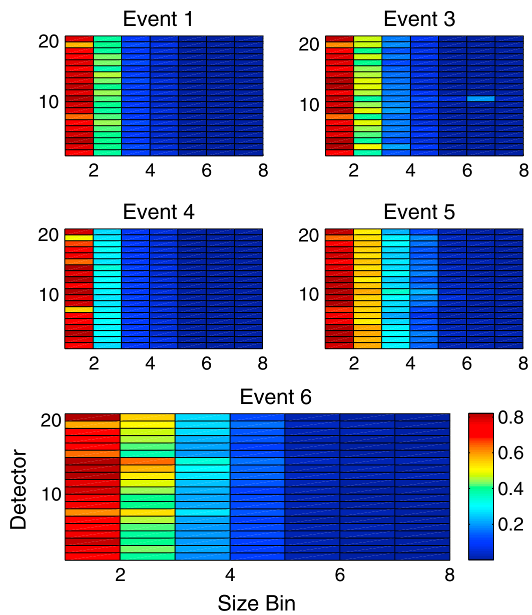

Figure 1. Plots of the superterminal fraction of drops as a function of drop size (horizontal axis) for each LPM (sequentially on the vertical axis). The first eight size bins have midbin drop diameters of 0.1875 mm, 0.3125 mm, 0.4375 mm, 0.625 mm, 0.875 mm, 1.125 mm, 1.375 mm, and 1.625 mm. The color shown indicates the fraction of drops detected as superterminal (following the color bar). Note the substantial agreement between detectors and the ubiquity of superterminal occurrence for small drop sizes. (Event 2 is not shown since not all LPMs were operational for this event.)

The data presented here come from six different rain events; summary of the event statistics are presented in Table 1. The 2DVD in these six events detected a total of over 1.5 million raindrops; the LPMs combined to detect over 22 million drops, making this data set over 2 orders of magnitude larger than that explored in *Montero-Martinez et al.* [2009].

3. Data Analyses

The authors of *Montero-Martinez et al.* [2009] defined a superterminal drop as any drop exceeding its expected terminal velocity by at least 30%. We use the same definition here. The terminal velocity for a drop was calculated using the ninth-order power law parameterization developed by *Foote and DuToit* [1969].

Figure 1 shows the calculated superterminal fraction for each of the LPMs in the five events where all detectors were operational. The midpoint diameters of the size bins shown are 0.1875 mm, 0.3125 mm, 0.4375 mm, 0.625 mm, 0.875 mm, 1.125 mm, 1.375 mm, and 1.625 mm.

Since the LPMs produce binned size and velocity data, all processing decisions were made in order to minimize the number of estimated superterminal drops so that our estimation of the fraction of superterminal drops is conservative. All drops associated with a particular size bin are assumed to have diameters equal to the midpoint of the size bin (this likely overestimates the sizes for most drops due to the skewness of the true drop size distribution). A drop mapped to a particular velocity bin was only considered superterminal if *all* velocities in the associated velocity bin exceeded the $v_{\mathrm{measured}} > 1.3 v_{\mathrm{terminal}}$ criterion.

Most notable in Figure 1 is that all instruments show qualitatively similar behavior for each storm, though event-to-event variability is notable. In all events, a large fraction of the small drops are detected at speeds above their terminal velocity. Further, this behavior is not spatially localized; instruments over 100 m apart see similar behavior.

The LPMs may not be the ideal instrument to characterize drop speed; Figure 1 shows some evidence that some of the detectors consistently see a larger superterminal fraction than others, suggesting that the detectors may have some biases. Also, the LPMs have only 22 size bins and only 20 velocity bins. Because of how they are binned, many "barely" superterminal drops may not be counted in this study. As a numerical example, a raindrop that has a diameter of 0.77 mm should, according to the parameterization of *Foote and DuToit* [1969], have a terminal velocity of 3.18 m/s and should be characterized as superterminal if it falls at a speed of at least 4.13 m/s. However, because of the binning structure, the 0.77 mm drop would be placed in a bin that contains particles from 0.75 to 1.00 mm. The midpoint of this bin is 0.875 mm with a terminal velocity of 3.57 m/s. For this size bin, a drop is characterized as superterminal if it reaches a speed of 4.64 m/s. The smallest velocity bin exceeding this value starts at 5.0+ m/s, so the hypothetical 0.77 mm drop must be falling at over 5.0 m/s to be categorized as superterminal. This is over 57% faster than the empirical expected terminal fall velocity of a 0.77 mm drop. In short, any drop that is measured to be superterminal in this way likely truly is falling substantially faster than expected.

The 2DVD provides a robust way to determine whether the superterminal detections are a spurious result of a flawed instrument. Figure 2 shows a comparison between LPM and 2DVD data. Note that the 2DVD

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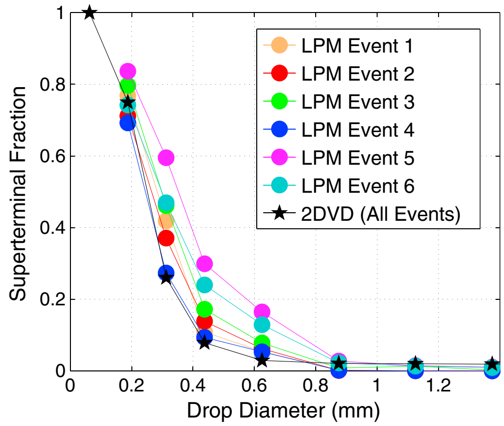

Figure 2. Superterminal drop fraction as a function of drop size. Note that there is substantial event-to-event variability that exceeds the detector-to-detector variability seen in Figure 1. The superterminal fraction seen by the 2DVD is comparable to those seen by the LPMs.

has one extra data point for very small drops that the LPMs are not able to resolve. The detection of only superterminal drops for this drop size is spurious; the 2DVD software automatically filters out any drops falling with a vertical velocity smaller than 0.5 m/s; thus, any detected drops less than 0.12 mm have to be superterminal. It is noteworthy that the plots for the two instruments largely agree with each other (and with the results given in *Montero-Martinez et al.* [2009]) despite the fact that each instrument has a different form factor and sensing volume. This is encouraging.

It is a little surprising that the 2DVD generally sees a lower fraction of superterminal drops than the LPMs when all data processing decisions associated with the LPM were utilized to underestimate the number of superterminal drops. However, the instruments do obtain the drop velocities via slightly different methods, and the differences may be due to a built-in bias associated with some of the instruments. Even though many raindrops were studied, all data here are presented from only a few storms; a more thorough investigation may enable better understanding of this behavior. No matter the ultimate cause of the differences between the instruments, it is clear that all detectors saw the same basic qualitative behavior and that both types of detector identified a substantial fraction of drops less then 1 mm in diameter as superterminal.

To definitively demonstrate that the observation of superterminal drops are not primarily due to breakup caused by large drops hitting the side of the instrument's opening, see Figure 3. The sensing volume of the 2DVD is (approximately) a square region. This region is in the center of a larger square opening. The entire opening is not visible to the detector; detection of a drop requires mutual observation in two separate cameras, neither of which covers the entire opening. A hypothetical drop hitting the edge of the opening, fragmenting, and falling through the observable part of the sampling volume would have to horizontally move a distance of at least 7.5 cm in the time it takes to vertically fall 4.5 cm. For a 0.5 mm drop falling with a vertical component of its velocity 30% faster than the drop's terminal velocity, this implies an average horizontal velocity of at least 4.4 m/s.

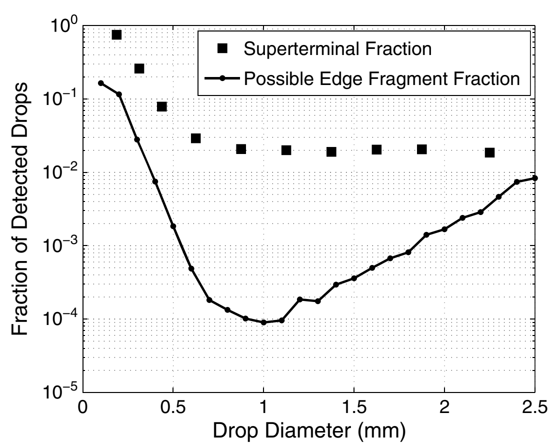

Figure 3. The squares indicate the superterminal fraction of drops as a function of drop size for the 2DVD (all events). The solid line shows the fraction of drops with a measured horizontal velocity sufficient to potentially have been the result of a fragmentation event on the edge of the detector. In all cases, the measured fraction of superterminal drops is substantially larger than could have been supported by instrument-created splashing alone.

The 2DVD is capable of identifying an approximate instantaneous horizontal velocity for each drop during detection. Since the relaxation time for each drop is substantially longer than the time it takes to traverse the detector, it can be determined for each drop if it is even possible that the drop could have originated from a fragmentation at the instrument's opening. The solid line shown in Figure 3 indicates the fraction of detected drops (from all events) that reported sufficient horizontal velocity to move at least 7.5 cm horizontally in the time it would take something falling vertically at $1.3v_t$ to travel 4.5 cm. It is important to note that this solid line *overestimates* the number of drops that may be classified as superterminal due to splashing since (i) drops with this horizontal velocity may have been detected in the middle of the detector where an even larger horizontal velocity

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would have been needed to suggest droplet origin at the detector edge and (ii) the drops measured with a horizontal velocity this large were not necessarily the detected superterminal drops. Even if drop fragmentation due to splashing on the instrument did cause some drop fragments to travel through the detector at a superterminal speed, the majority of detected superterminal drops could not have been created by this mechanism.

4. Conclusions

Measurements were taken from 22 optical disdrometers. The results are consistent with those seen by *Montero-Martinez et al.* [2009], despite using completely different instruments. A sizeable fraction of natural drops smaller than 1 mm in diameter appear to fall faster than their terminal velocity in still air. It is clear that these superterminal drops, if they are created due to large drop fragmentation, are not caused by fragmentation on the measurement instrument. These superterminal drops may have impacts on rain accumulation estimation from radar, erosion parameterization, and drop size distribution estimation. Further studies ascertaining the natural abundance of these drops and accounting for the impact of superterminal drops in rain microphysics should be conducted.

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