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Scaling properties of raindrop size distributions as measured by a dense array of optical disdrometers

Michael L. Larsen *, Timothy B. Hayward [1], Joshua B. Teves

Department of Physics and Astronomy, College of Charleston, SC 29424, USA

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SUMMARY

A dense network of optical disdrometers with 1 min resolution was utilized through the winter months of 2013–2014 in South Carolina, USA, to explore the manner in which box-counting fractal dimension is related to drop size. Ten storms of a duration exceeding eight hours were selected for detailed analysis. It was discovered that detector-to-detector variation within each storm was negligible, though storm-to-storm variability could be substantial. The box-counting fractal dimension was found to decrease with increasing drop size, suggesting that large drops are more temporally clustered than small drops. Implications for raindrop sampling are discussed.

1. Introduction

The study of rainfall microstructure has been an active area of research for decades. A central focus for most of this time period has been the study and interpretation of the raindrop size distribution (RSD) (see, e.g., Atlas, 1964; Feingold and Levin, 1986; Jameson and Kostinski, 1998, 2001; Jameson et al., in press; Joss and Gori, 1978; Kostinski and Jameson, 1999; Laws and Parsons, 1943; Marshall and Palmer, 1948; Srivastava, 1971; Ulbrich, 1983, for just a few of the many investigations devoted to RSDs that span the era from the 1940s to the present). The focus on RSDs is principally motivated by the links between the statistical moments of the raindrop size distribution and other variables of physical interest including radar reflectivity, rain rate, liquid water content, drop number density, and drop kinetic energy (see, e.g., Uijlenhoet et al., 2006).

One of the results from the study of rain microstructure is that RSDs often exhibit highly variable behavior over a wide range of temporal and spatial scales (see, e.g., Jaffrain et al., 2011; Jameson and Kostinski, 2000; Jameson et al., in press). Spatial and temporal variability of rainfall and RSDs has impacts on the study of many atmospheric phenomena. To name just a few examples, spatial clustering aloft can influence droplet growth (Kostinski and Shaw, 2005), collision-induced breakup (McFarquhar, 2004), and radiative transmission (Kostinski, 2001).

The spatio-temporal variability of RSDs also presents challenges to the rain investigator seeking to relate point rainfall measurements to extended spatial areas like those utilized in ground validation and/or satellite studies (Tapiador et al., 2012). If point measurements are to be effectively utilized in studies associated with geographically-relevant spatial scales, a more complete quantitative characterization of the natural spatial and temporal variability of rain is necessary (Kostinski et al., 2006).

The detected presence of ground-based RSD temporal variability also has implications for RSD measurement and reporting. In particular, it has been noted that the presence of inhomogeneities in natural rain can influence the interpretation of measured RSDs (Jameson and Kostinski, 2001). This is one primary motivation for efforts to characterize raindrop size-dependent clustering (see, e.g., Kostinski et al., 2006; Larsen et al., 2005; Larsen, 2006; Uijlenhoet et al., 2006). If drops exhibit size-dependent clustering, it is conceivable that an enhanced RSD sampling strategy could be constructed that has some property (e.g. sampling time associated with measurement) that would be raindrop size-dependent as well.

* Corresponding author.
E-mail address: larsenml@cofc.edu (M.L. Larsen).
[1] Present address: Department of Physics, College of William and Mary, Williamsburg, VA 23187, USA.

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Although a variety of different formalisms have been utilized to characterize RSDs (see, e.g., Larsen (2006)), many investigators in the microphysical rain community have recently used scaling (fractal or multifractal) statistical measures (for a small subset of studies utilizing scaling approaches see, e.g., Gupta and Waymire (1990), Larsen et al. (2005), Lavergnat and Golé (1998), Lovejoy and Schertzer (1990), Peters et al. (2002), and Zawadzki (1995)). This approach is very well suited for time-series analysis, has shown recent success in describing temporal rainfall variability in a dense (~10 m × 8 m) network of rain gauges (Larsen et al., 2010), and – when using the particularly simple approach of box-counting – enables the investigator to quantify a great deal of information associated with statistical structure into a single numerical parameter (the "box-counting fractal dimension").

In this manuscript, a simple box-counting scaling approach is utilized to examine data from a dense network of optical disdrometers with 1 min temporal resolution. It is shown that there is unambiguous evidence for raindrop size-dependent clustering behavior. The clustering behavior (when characterized with the box-counting fractal dimension) exhibits spatial uniformity over the ~100 m of the array for each studied storm, but storm-to-storm variability can be substantial.

2. Scaling formalism

In the context of atmospheric research, ideas and methods associated with statistical scale invariance have been widely applied. The terminology can refer to an extremely broad range of theoretical structures. The term "fractal dimension" can refer to the Hausdorff dimension, information dimension, correlation dimension, box-counting dimension, or any number of other measures (Peitgen et al., 1992). Additionally, multifractal analysis is rather popular in the hydrological sciences and may ultimately allow deeper insight into the nature of the data. This study constitutes a first step in the investigation of scaling properties of these data via use of the simple-scaling box-counting dimension.

The statistical structure utilized here follows the basic model outlined in Knyazikhin et al. (2005), Larsen et al. (2005), and Zawadzki (1995) and is built around the formula

$$N(\tau) = A\tau^{-f_d}. \quad (1)$$

Here, $N(\tau)$ is the number of disjoint time intervals of duration τ containing at least one "event," A and f_d are fitted statistical parameters, and τ is a time interval that can span from the resolution of the measuring instrument to the total duration of the data set. Within this context, f_d is interpreted as the "fractal dimension" of the data. (The box-counting dimension is used in this study because of its easy implementation, relatively low computational requirements (Fernández-Martínez and Sánchez-Granero, 2012; Foroutan-pour et al., 1999), and to enable comparison to other rain studies (Larsen et al., 2005, 2010; Zawadzki, 1995).)

The reader may have noticed that the term "event" is left ambiguous in the above expression defining f_d. The natural question follows: what quantity is scaling? In Larsen et al. (2005), individual rain drop arrivals (independent of size) were used to define an "event". In Larsen et al. (2010), tipping-bucket rain gauge tiptimes (associated with the times total rain accumulation reached an integer multiple of a hundredth of an inch) were used as "events". Both of these studies found some evidence to suggest scaling behavior, but – due to the analysis carried out – neither study was able to directly resolve scaling properties as they were related to RSDs.

Here, an "event" will be construed as the detection of a rain drop by an optical disdrometer in a particular size bin. Thus, a data record from a single disdrometer allows for investigation using the equation

$$N(\tau) = A(D)\tau^{-f_d(D)}, \quad (2)$$

where $N(\tau)$ indicates the number of disjoint time intervals of duration τ containing at least one rain drop associated with some diameter bin D. $A(D)$ and $f_d(D)$ then become fitting parameters that are functions of diameter D.

This study is primarily devoted to exploring the properties and behavior of $f_d(D)$. In particular, the following four questions are investigated. (1) Does $f_d(D)$ vary from detector to detector in a single storm? (2) Does $f_d(D)$ vary from storm to storm? (3) Is $f_d(D)$ related to mean rain rate, number of drops in the storm, storm duration, or peak rainfall intensity? (4) Does the general structure of $f_d(D)$ reveal anything about the drop size distribution and its fluctuations?

3. Experimental setup

To explore the scaling properties of RSDs as described above, data were utilized from a dense array of optical disdrometers located near Hollywood, South Carolina, USA, at 32°44′26″N, 80°10′36″W. This array is located in the South Carolina Lowcountry region, which has a humid subtropical climate (Köppen classification Cfa).

Annual rainfall can vary substantially in this region – a substantial fraction of the annual rainfall can come from tropical storms whose number and intensity vary greatly from year to year – but annual average precipitation is around 130 cm. The array has been constructed on land about 20 km North of the Atlantic coast.

The array of disdrometers includes 21 Thies Laser Precipitation Monitors (hereafter LPMs) (Frasson et al., 2011). The LPMs were deployed in three "arms" as shown in Fig. 1.

This investigation is a small part of another study devoted to understanding rain microphysics on spatial scales smaller than a typical weather radar pixel (see, e.g., Jameson et al., submitted for publication, in press; Larsen et al., 2014; Larsen and Teves, in press). Because of the overarching project goals, the entire disdrometer array has been constructed to fit within a 100 m × 100 m area, with no two detectors separated by a distance exceeding 125 m.

Each of the LPMs transmits a "data telegram" every minute which reports the number of detected raindrops and assigns each drop to a size and velocity bin. There are 22 non-uniform,

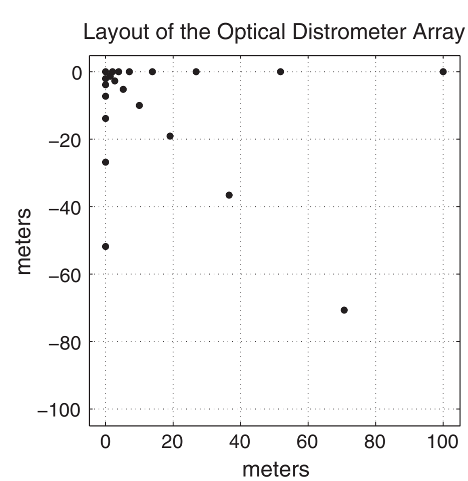

Fig. 1. An illustration of the general layout of LPMs in the instrument array. Each dot indicates the position of a detector. The spacing between detectors is scaled logarithmically to allow for the exploration of multiple spatial scales with a modest number of detectors.