Investigation of Raindrops Fall Velocity During Different Monsoon Seasons Over the Western Ghats, India

Subrata Kumar Das1, Sibin Simon2,3, Yogesh K. Kolte1,4, U. V. Murali Krishna1, Sachin M. Deshpande1, and Anupam Hazra1

1Indian Institute of Tropical Meteorology, Pune, India, 2Department of Atmospheric Sciences, Cochin University of Science and Technology, Cochin, India, 3ESSO - National Centre for Polar and Ocean Research, Goa, India, 4Atmospheric and Space Science, Savitribai Phule Pune University, Pune, India

Abstract Using the Two-Dimensional Video Disdrometer measurements, we investigated the fall velocity of raindrops at Mahabaleshwar (17.92°N, 73.6°E, ~1.4 km above mean sea level, AMSL), a tropical site on the Western Ghats of India. The analysis is for different seasons during 2012–2015. To increase the reliability and accuracy of analysis, the raindrops with diameters in the range 0.5–2 mm and horizontal wind speed < 2 m s−1 are considered. The observed raindrop fall velocities have been corrected for the effect of air density. The ratio between the observed velocity and calculated terminal velocity is considered for estimating superterminal (positively skewed; higher than terminal velocity) and subterminal (negatively skewed; lower than terminal velocity) raindrops. The distribution of these skewed raindrops and its relationship with rain rate, drop diameter, and axis ratio for different seasons has been examined. Results indicate the presence of superterminal and subterminal raindrops in definite proportion in all the season with a majority of the drops have a diameter less than 1 mm. It is found that most of the superterminal raindrops occur at rain rates below 5 mm hr−1, while subterminal raindrops are relatively higher above this rain rate. It is observed that the superterminal raindrops are usually small in size and prolate in shape, while the subterminal raindrops are relatively large and oblate in shape. The diurnal variation of these raindrops during different seasons is also studied.

1. Introduction

Knowledge of raindrop terminal velocities from their size distributions is important in cloud physics for modeling different physical processes like breakup and coalescence, radar measurements, soil erosion studies, and hydrological applications (Doviak & Zrnic, 1993; Collier, 1996; Salles & Creutin, 2003; Montero-Martínez et al., 2009). Several formulations have been developed to find the relation between raindrop diameter and terminal speed (Beard, 1976; Testik & Barros, 2007). The most extensively used form of the fall velocity (Vf)-drop diameter (D) relationship was reported by Atlas et al. (1973), which was formulated from the terminal velocity measurements of Gunn and Kinzer (1949) under calm laboratory conditions. However, in the natural laboratory-like atmosphere, the distribution of raindrop speeds likely to be slightly more complicated and always cannot be represented in terms of drop diameter (Villermaux & Eloi, 2011). Studies have shown that apart from raindrop size, several other factors can influence the raindrop fall velocity (Niu et al., 2009). For instance, updrafts and downdrafts air motion within the rain cell (Battan, 1964), turbulence (Finsky & Khain, 1997), and raindrop breakup/coalescence (Montero-Martínez et al., 2009) can have considerable influences on the raindrop fall velocity.

In the last decade, several studies revealed that raindrops sometimes do not necessarily fall at terminal velocities, which is calculated using relation with drop diameter (Bringi et al., 2018; Larsen et al., 2014; Montero-Martínez et al., 2009; Testik et al., 2006; Thurai et al., 2013). Montero-Martínez et al. (2009) found that the intermediate raindrops fall faster than the expected fall speeds. They attributed this to the raindrop breakup processes. Thurai et al. (2013) observed the broadening of fall speed distribution with a significant skewness during the passage of an intense convective rain event, which is due to the asymmetric horizontal mode of oscillations of raindrops. Larsen et al. (2014) and Montero-Martínez and García-García (2016) evidenced the presence of superterminal (higher than terminal velocity) and subterminal (lower than terminal velocity) fall speeds in intense rain events. More recently, Bringi et al. (2018) also showed the existence of superterminal and subterminal raindrops from an optical probe and Two-Dimensional Video Disdrometer.
Thus, the raindrops may not fall at their terminal velocity except under calm conditions.

Understanding the raindrop size distributions (DSDs) has a variety of applications, including rainfall retrievals using remote sensing instruments (e.g., ground-based and space-borne weather radars), hydrological and climate modeling (e.g., Bringi & Chandrasekar, 2001; Testik & Barros, 2007), rain scavenging of aerosol particles, soil erosion (e.g., Uijlenhoet et al., 2003; Uijlenhoet & Sempere Torres, 2006), and rain microphysics (e.g., Das et al., 2017; Konwar et al., 2014; Krishna et al., 2016). The raindrops fall velocity deviations from their calculated fall velocity represent a problem for determining DSDs from certain instruments like Joss-Waldvogel disdrometer, and vertically pointing Doppler radar measurements, and the subsequently derived radar reflectivity-rainfall intensity relations. For instance, the fundamental principle of Joss-Waldvogel disdrometer is to convert the measurement of the impact energy of falling drops (under the assumption that all drops travel at terminal velocity) to the size of the diameter of each drop (Joss & Waldvogel, 1967). Therefore, the misrepresentation of raindrops fall velocity can lead to enormous errors in the DSD.

From the previous studies, it is shown that the fall velocities of raindrops show a wider distribution with a significant skewness toward lower fall speeds (Thurai et al., 2013) in some cases and toward higher fall speeds in other cases (Montero-Martínez et al., 2009). Thus, the concept of a fall speed distribution for a raindrop of a given diameter might need to be considered. For this, the simultaneous measurement of raindrop volume, fall speed, and shape are essential. A 2DVD is the only instrument that is capable of providing such data (Schönhuber et al., 2008) for small to moderate-sized raindrops (below 2 mm) under calm wind conditions (Bringi et al., 2018). In the present study, we investigated the fall velocity measurements of raindrops over Mahabaleshwar (17.92°N, 73.6°E, ~1.4 km AMSL), Western Ghats (WGs) of India using 2DVD measurements. Using long-term 2DVD measurements, we try to address the fraction of superterminal and subterminal raindrops that occurs and its seasonality, and the dependence of superterminal and subterminal velocities on raindrop size, shape, and rain rate. The paper is organized as follows: introduction to the 2DVD system and its main technical specifications and methodology and other data set used in the analysis are described in section 2. The climatological features of the study region are illustrated in section 3. Results and discussion are provided in section 4. Finally, section 4.5 summarizes the major findings of this work.

2. Data and Methodology

The present study uses 4 years (2012–2015) of measurements from 2DVD installed at the High Altitude Cloud Physics Laboratory (HACPL; 17.92°N, 73.6°E, ~1.4 km AMSL), Mahabaleshwar in the WGs region. The topography of the study region is shown in Figure 1. The 2DVD is an optical-type disdrometer (two cameras orthogonally placed) that measures the raindrops size, shape, and fall velocity of individual drops that fall through its virtual measuring area of 10 × 10 cm² (Schönhuber et al., 2007, 2008). The 2DVD sample the raindrops at a time interval of 1 min with a nominal resolution of 0.2 mm. The detailed technical description can be found in the user manual of 2DVD provided by Joanneum Research, Austria. The 2DVD is regularly calibrated using the metal sphere. This calibration allows for the correctness of the size of the raindrops as well as the vertical distance between the optical planes to be precisely measured, thereby ensuring accurate fall speed measurements (Gatlin et al., 2015). The 2DVD’s accuracy in the measurement of raindrop size and fall velocity is documented in Thurai et al. (2007, 2009) and Bernauer et al. (2015). In addition to 2DVD measurements, the meteorological parameters like temperature, relative humidity, surface wind speed, and direction measured by the Automatic Weather Stations (AWS) deployed at HACPL, Mahabaleshwar is also utilized. DYNALAB, India, developed the AWS.

The presence of superterminal raindrops was observed by several researchers (Donnadieu, 1979; Hauser et al., 1984; Hosking & Stow, 1991; Kruger & Krajewski, 2002). However, they discarded them as
instrumental outliers. Montero-Martínez et al. (2009) showed that the raindrops fall speed shows positive and negative skewness from their terminal velocity, which is calculated using relation with drop diameter (Atlas et al., 1973). They defined these raindrops as superterminal drops, with fall speed 1.3 times (30% above) the calculated terminal velocity (positive skewness from normal distribution) and subterminal drops, with fall speeds, 0.7 times (30% below) (negative skewness from normal distribution) the calculated terminal velocity using Atlas et al. (1973) drop diameter relation. In the present study, the superterminal and subterminal raindrops are defined using the criteria provided by Montero-Martínez et al. (2009).

3. Climatological and Geographical Description of the Study Site

To examine the background climatic conditions over the study region, the meteorological parameters like temperature, relative humidity, rainfall accumulation, wind speed, and wind direction are presented in Figure 2 and Figure 3. These meteorological parameters are obtained from AWS observations collected during 2012 to 2017 over HACPL, Mahabaleshwar. Figures 2a–2c show the monthly mean variation, and Figures 2d–2f show the seasonal mean variation of temperature, relative humidity, and rainfall, respectively, for the period 2012–2017. Vertical bars represent the standard deviation from the mean value.

3.1. Temperature

From Figure 2a, it can be seen that the temperature usually varies between 18 and 26 °C over Mahabaleshwar during different months in a year. April is the warmest month with temperature up to 26 °C, while the lowest temperature is in August with an average temperature of 18–19 °C. Figure 2d shows that the hottest season is premonsoon (March to May), while the coolest season is monsoon (June to September). During postmonsoon (October and November), the temperature is above 20 °C and winter (December to
February) is generally cooler, with temperatures lower than 21 °C. There is a 7–8 °C difference between the maximum and minimum temperatures for different months in a year. September and February show the maximum standard deviation from their mean value.

### 3.2. Relative Humidity

Monsoon months have high relative humidity values, almost above 95%, with July having 99%, which is the highest among all the months. Warm and humid air with high moisture content from south of the Arabian sea strike the WGs during monsoon season make a highly humid atmosphere during this season. Premonsoon season shows a sharp increasing trend during the end of season, and relative humidity values reach up to 90% at the beginning of June. March is the driest month with very low relative humidity, which is less than 40%. During the postmonsoon season, the graph shows negative sloped shapes, which indicate the decreasing nature of relative humidity. Winter is the driest season, and the relative humidity is always below 50% during this season. The standard deviation is higher for February–April months, which is the beginning of the premonsoon season.

Figure 3. Wind rose for (a) premonsoon, (b) monsoon, (c) postmonsoon, and (d) winter over HACPL during the period from 2012 to 2017.
3.3. Rainfall

Rainfall is the most prominent feature of this region, with an average annual rainfall above ~5500 mm during a year. Monsoon season itself contributes about 90% of the total rainfall. August is the most precipitated month, and July and August contribute above 50% of annual rainfall. The standard deviations during the monsoon months are high, indicating large variability during this season. The larger variability in the monsoon rainfall is associated with the intra-seasonal oscillations of the summer monsoon. December is the least precipitation month. Rainfall varies around 1500 mm between the driest and wettest month. Winter is the driest season with the least amount of rainfall. Postmonsoon and premonsoon seasons also contribute a significant amount of rainfall but is less when compared to rainfall accumulation during monsoon season.

3.4. Wind Speed and Direction

Figure 3 shows the wind rose plot for different seasons (a) premonsoon, (b) monsoon, (c) postmonsoon, and (d) winter during the period from 2012 to 2017. The wind rose represents the distribution with which the wind blows from a given direction (N = north, S = south, E = east, and W = west). The length of each wedge indicates the frequency, with the distance between two concentric circles representing a frequency of 5% for premonsoon, monsoon, and winter, while 10% for postmonsoon. The color bar indicates wind speed. Over the study region, winds are mainly concentrated on the southwest (SW) and southeast (SE) direction, in which each season has a definite wind pattern that is shifting from one season to another. Also, the mean wind speed always remains to be calm to moderate (<10 m s\(^{-1}\)) in all seasons. During premonsoon, wind direction is little widespread, mainly directed between west and east directions. Low wind speeds about 2–4 m s\(^{-1}\) are in the southwest direction and about 4–6 m s\(^{-1}\) in the southeast (SSE) direction. Monsoon season is dominant with winds from the Arabian Sea directed from southwest (SW) direction. This season experiences higher wind speed than other seasons ranging from 1–10 m s\(^{-1}\) and most of the wind having a moderate velocity in the range 4–6 m s\(^{-1}\). During postmonsoon, the wind is directed from the southeast (SE) direction with varying wind speeds of 1–6 m s\(^{-1}\). In winter, the wind is directed usually from the south (S) with speed ranging from 2–4 m s\(^{-1}\).

4. Results and Discussion

The 2DVD measurements during 2012–2015 are used to retrieve raindrops size and fall speed. Figure 4 shows the total number of rainy days observed by 2DVD each month during 2012–2015. In the present analysis, rainy days are considered when there are at least five consecutive 1-min 2DVD samples present with rain rate greater than 0.1 mm hr\(^{-1}\). The rainy days are classified when both 2DVD, and AWS measurements are available simultaneously. The winter season is not included in the analysis, as the total rainfall (rain events) is minimal and insignificant. It can be seen that the monsoon season (June–September) has the highest number of rainy days, which includes 76% of the total rainy days, displaying the unique feature of monsoon in this region. July is the month with the highest number of rainy days. Premonsoon month May has the least rainy days. Monsoon season with a large amount of rainfall in the study region enriches this season with a very high number of data points. Postmonsoon (October–November) has 27 rainy days, which is 16% of the total rainy days. Delay in the monsoon withdrawal contributes to the higher availability of rain events during postmonsoon. Premonsoon witnessed with thunderstorm and large convective activities (Roy Bhowmik et al., 2008), which contributes an appropriate amount of rain during this season.

To examine the distribution of superterminal and subterminal raindrops, the total number of data used for the analysis must be statistically significant. Figure 5 shows the total number of raindrops observed during different seasons. The raindrops with a diameter less than 0.5 mm are excluded from the analysis, as the smallest calibrated sphere used for 2DVD is 0.5 mm. A huge number of raindrops (~10\(^7\)) are present during the monsoon season due to the abundance of rainy days during monsoon season. In premonsoon, there are about 8 \times 10^4 raindrops, which is least among the other seasons, but it is a convenient number to have the
statistical calculation of fall velocity during premonsoon season. Postmonsoon is also rich in the number of drops. The large data set for each season is very useful for the study of rain microphysics.

Raindrop fall velocity is affected by several atmospheric conditions and by airflow over the hydrometeor, drop oscillations, deviation of trajectory, transverse drifts with respect to vertical, etc. (Testik & Barros, 2007). The presence of horizontal wind makes deviation in the fall velocity of a raindrop. Recently, Bringi et al. (2018) observed that a 2DVD could provide reliable fall speed measurements for raindrops below 2-mm diameter under calm wind conditions (horizontal wind speed less than 2 m s\(^{-1}\)). Therefore, the raindrops observed when horizontal wind speed less than 2 m s\(^{-1}\) (measured using AWS) and diameter less than 2 mm (from 2DVD observation) are considered for the analysis. This will be called as “constraint condition” in the latter part of the paper. The instrument splashing effects can be ruled by restraining the study for calm wind conditions (wind speed <2 m s\(^{-1}\)).

Figure 6 illustrates the number of rain events before and after the constraint condition is applied. Here, the rain event corresponds to 1-min data from 2DVD by satisfying the definition of a rainy day, as discussed above. The figure shows that there is an overall reduction in the data set for all seasons when the data is constrained for horizontal wind speed (<2 m s\(^{-1}\)) and drop diameter (<2 mm). The effect of thunderstorm wind gusts, large-sized drops, and high-velocity monsoon winds (LLJ) (Roy Bhowmik et al., 2008; Joseph & Raman, 1966) on raindrop size and shape are mostly removed by applying the constraint condition. Premonsoon season, which is lowest in the number of rain events, still has about 500 min of observations during rain.

Rainfall pattern over the WGs varies for different seasons, and there are variations in prevailing wind conditions, DSDs, etc. Figure 7 shows the normalized distribution of rain rates before and after applying the constraint condition in different seasons. It shows that rain events occur at different rain rates (up to 60 mm hr\(^{-1}\)) during premonsoon. After the constraint condition is applied, most of the data constricted to low rainfall (≤10 mm hr\(^{-1}\)) rates. This shows that there is a possibility of high wind gust and large-sized raindrops during thunderstorms, which are one of the typical features of premonsoon rain (Roy Bhowmik et al., 2008). Thus, most of the data eradicated due to the constraint condition in the premonsoon season. Even in the absence of high wind gust, the monsoon season shows a wide range of rain rate distribution, up to 140 mm hr\(^{-1}\). The distribution also shows a decreasing trend with the increase of rain rates. It is observed that the total data set, and constrained data set are in the same proportion in the distribution. This indicates the homogenous distribution of raindrops and wind velocity in all rain rates, which is the unique feature of monsoon (Narayana Rao et al., 2009). In the postmonsoon season, the rain rates are dispersed and concentrated on high and low rain rate extreme values. High rain rate values are cleared out by the constraint condition, and low rain rates dominate the constrained data. High rain rates are due to thunderstorm rain events. Overall, after applying constraint conditions, data converged mostly into low rain rate ranges.

4.1. Effect of Air Density on Raindrop Fall Velocity

Previous studies showed that the effect of air density on raindrop terminal velocity is not negligible and needs to be accounted (e.g., Foote & Du Toit, 1969; Niu et al., 2009). The standard equation for raindrop terminal velocity was derived at sea level surface, with an air density of 1.23 kg m\(^{-3}\). However, the measurement site, Mahabaleshwar, is at higher altitude
Therefore, the raindrop terminal velocity at higher altitude may be higher than the corresponding Gunn-Kinzer’s data (Pruppacher & Klett, 1998). To quantify the effect of air density on raindrop fall velocity, a correction factor is to be multiplied in the right-hand side of the fall velocity equation of Atlas et al. (1973). Beard (1985) provided a correction factor for the raindrop terminal velocity at higher altitude and is expressed as follows:

$$V_t = V_0 \left( \frac{\rho_a}{\rho_0} \right)^m$$

(1)

Where $V_0$ (m s$^{-1}$) is the fall velocity of the raindrop of diameter $D$ (mm) in the standard atmosphere at the sea level, say, the Gunn-Kinzer terminal velocity; $\rho_a$ is the air density at the Mahabaleshwar site, and $\rho_0$ is the air density at the sea level. The exponent “$m$” is the unknown in equation (1), and it depends on the raindrop diameter (Beard, 1985).

$$m(D) = 0.375 + 0.025D$$

(2)

Table 1 shows the altitude adjusted fall velocity for various drop diameters during different seasons. Recently, Bringi et al. (2018) presented the expected terminal velocity of raindrops at 1.4-km altitude, which is well compared with our findings. To compare our results with other regions but at the same altitude level, we considered Greeley (at ~1.4 km), Colorado (Bringi et al., 2018). Table 2 shows the raindrops fall velocity measured from 2DVD over Mahabaleshwar, WGs, and Greeley, Colorado. It is seen that the fall velocity measured from 2DVD compares well with the theoretically estimated value after applying the altitude correction (Table 1) and with the Greeley 2DVD measurements.
4.2. Evidence for Raindrops That Deviate From Terminal Velocity

The studies for evaluation of superterminal and subterminal drops were attempted by various authors (Bringi et al., 2018; Larsen et al., 2014; Montero-Martínez et al., 2009; Montero-Martínez & García-García, 2016; Thurai et al., 2013). These drops are defined by the deviation of their observed velocity from calculated terminal velocity. In this work, the drop’s terminal velocity has been adjusted for height by considering the air density (Beard, 1985). The ratio between observed fall velocity ($V_{2DVD}$) and calculated terminal velocity (theoretical; $V_t$) is taken into consideration. The raindrops with $V_{2DVD}/V_t > 1.3$ are termed as superterminal, and $V_{2DVD}/V_t < 0.7$ are considered as subterminal drops (Montero-Martínez et al., 2009).

Figure 8 shows the normalized distribution of $V_{2DVD}/V_t$ for different seasons. It is clear that about 7% of raindrops have skewness from calculated terminal velocity using equation (1) during the premonsoon season. Among that, only 2% of raindrops are superterminal, and 5% are subterminal raindrops. Most of the raindrops (93%) lying in the expected velocity range, which follows the terminal velocity equation. However, during the monsoon season, a substantial number of drops show deviations from the terminal velocity. About 18% of raindrops are in the skewed region with 6% of superterminal and 12% of subterminal drops. In the WGs region, during monsoon season, clouds cannot grow higher because of the presence of high wind shear. However, the occurrence of high rainfall and rain events points out that the presence of collision-coalescence processes inside these clouds, which is essential for the growth of the cloud drops into raindrops (Konwar et al., 2014). Due to an efficient collision and coalescence process in low-level clouds, drops grow to larger sizes and fall with velocity smaller than expected. In addition, the airflow over raindrops can also affect the fall velocity of the raindrops (Jones et al., 2013). Raindrops with diameters >1 mm undergo oscillations (Testik et al., 2006). The higher updraft speeds over the orographic regions (WGs) enhances these drop oscillations and results in smaller terminal velocities for the raindrops (Montero-Martínez & García-García, 2016). Further, breakup processes produce a large number of small fragments that persist the same speed of their parent drop, so fall faster than expected velocity depending on the diameter of the drop (Montero-Martínez et al., 2009). Due to these microphysical processes, significant fractions of superterminal and subterminal raindrops are detected in the WGs region. The postmonsoon season has about 14% of total drops violating the terminal velocity criteria, of which 2% are superterminal, and 12% are subterminal raindrops. Most of the drops fall in the terminal velocity region, but the number of skewed raindrops cannot be

![Figure 8](image-url)

**Figure 8.** Normalized distribution of $V_{2DVD}/V_t$ for different seasons. The dashed red line marked the boundary for the superterminal and subterminal velocity of raindrops.

| Drop diameter (mm) | Premonsoon | Monsoon | Postmonsoon | Bringi et al. (2018) (Greeley) |
|-------------------|------------|---------|-------------|--------------------------------|
|                   | Mean       | Std. dev. | Mean       | Std. dev. | Mean       | Std. dev. |
| 0.6–0.8           | 3.151      | 0.713    | 2.964      | 0.850    | 2.850      | 0.832     | 2.5 ± 0.8  |
| 0.8–1.0           | 3.968      | 0.663    | 3.781      | 0.916    | 3.700      | 0.946     | 3.3 ± 0.9  |
| 1.0–1.2           | 4.771      | 0.589    | 4.567      | 0.907    | 4.544      | 0.878     | 4.1 ± 0.9  |
| 1.2–1.4           | 5.397      | 0.522    | 5.153      | 0.867    | 5.166      | 0.788     | 5.0 ± 0.8  |
| 1.4–1.6           | 5.906      | 0.478    | 5.729      | 0.804    | 5.748      | 0.742     | 5.7 ± 0.7  |
| 1.6–1.8           | 6.401      | 0.469    | 6.281      | 0.760    | 6.292      | 0.697     | 6.2 ± 0.7  |
| 1.8–2.0           | 6.872      | 0.451    | 6.813      | 0.709    | 6.835      | 0.660     | 6.6 ± 0.8  |

**Table 2** Observed Fall Velocity ($m s^{-1}$) From 2DVD For Various Drop Diameters for Different Seasons

**Note.** The observation made from 2DVD over Greeley (at ~1.4 km), Colorado, is also shown (Bringi et al., 2018).
neglected. Due to the extended withdrawal of monsoon, postmonsoon also shows a similar pattern of monsoon rain events and have a relevant amount of superterminal and subterminal raindrops.

The above analysis reveals a few general features of the fall velocity of raindrops. In all seasons, the majority of raindrops following the terminal velocity criteria, but a significant amount of raindrops are deviating from the terminal velocity criteria with monsoon having the highest amount of these skewed drops. In a natural rain event, a substantial asymmetry is present in fall speed distribution as expected. In the present study, we observed that the negative deviations (subterminal raindrops) are higher than positive deviations (superterminal raindrops) during all the seasons. Hence caution to be taken while considering the raindrop’s terminal speeds.

4.3. Superterminal and Subterminal Velocity Relation With Rain Rate

The distribution of superterminal and subterminal raindrops at different rain rates is shown in Figure 9. In premonsoon, low rain rates are predominant (mostly below 10 mm hr\(^{-1}\)) after applying the constraint condition. All the superterminal drops are present below 10 mm hr\(^{-1}\), and among them, 65% are present below 5 mm hr\(^{-1}\). Most of the subterminal drops are also present below 10 mm hr\(^{-1}\) and are dominant below 5 mm hr\(^{-1}\). However, a small number of subterminal drops present above 30 mm hr\(^{-1}\). During the monsoon season, the rain rate varies widely up to 100 mm hr\(^{-1}\). However, the distribution peaks at lower rain rates and then decrease exponentially. The dominance of superterminal raindrops is higher in low rain rates (5 mm hr\(^{-1}\)), and subterminal raindrops are dominant for the rest of the rain rates. Postmonsoon also shows higher rain rates up to 100 mm hr\(^{-1}\), but such an exponential decrease was not observed in this season. There is a kink in raindrop distribution when rain rate is at 40 mm hr\(^{-1}\), which is evident for strong rain events in the postmonsoon season. The distribution of superterminal and subterminal raindrops shows a decreasing trend with an increase in rain rate. The subterminal (superterminal) raindrops dominate the superterminal (subterminal) raindrops at higher (lower) rain rates in the postmonsoon season. Further, the superterminal raindrops are higher at higher rain rates compared to other monsoon seasons.

It is clear from the above discussion that the superterminal and subterminal raindrops exist at all rain rates during all the seasons. However, a small difference exists among them. In all the seasons, both the superterminal and subterminal drops decrease with an increase in rain rate. This result is contradicting the results of Montero-Martinez et al. (2009), which states the superterminal raindrops increases with an increase in the rain rate. In general, superterminal raindrops dominates the subterminal raindrops in lower rain rates (<5 mm hr\(^{-1}\)), and in the rest of the rain rates, the subterminal raindrops show the supremacy. However, it is opposite in the premonsoon season. The presence of a large number of small (large-sized) raindrops in lower (higher) rain rates may be responsible for the abundance of superterminal (subterminal) raindrops.

Figure 9. Normalized distribution of superterminal and subterminal raindrops for different rain rates (mm hr\(^{-1}\)) during different seasons.
4.4. Relation of Superterminal and Subterminal Velocity With Raindrop Diameters

The terminal velocity of a raindrop is calculated as a function of drop diameter (Atlas et al., 1973; Gunn & Kinzer, 1949; Mitchell, 1996). Hence, it is important to examine the variations in the fall velocity with raindrop diameter for superterminal and subterminal raindrops over different diameter ranges. Figure 10 shows the normalized distribution of fall velocity as a function of raindrop diameter for superterminal and subterminal drops during different seasons. In the premonsoon season, the superterminal and subterminal drops show an exponential decrease with an increase in diameter. The superterminal raindrops usually exist up to a diameter of 1.6 mm. The distribution of superterminal raindrops is higher below 0.6 mm diameter compared to subterminal drops. Subterminal raindrops show dominance over superterminal raindrops at a diameter range above 0.6 mm. During monsoon, both subterminal and superterminal raindrops present up to a diameter of 1.8 mm. A major portion of superterminal and subterminal raindrops exist below 1 mm, and it shows a decreasing trend as diameter increases. The maximum fraction of superterminal raindrops is seen at a diameter of 0.5 mm, where it exceeds the subterminal drops. Postmonsoon also shows a similar pattern as monsoon season in which superterminal raindrops concentrated in smaller diameter range and subterminal raindrops are widespread over larger diameter range.

It is evident here that the distribution of superterminal and subterminal drops vary with the drop diameter (Larsen et al., 2014). Superterminal raindrops are mainly observed at 0.5-mm diameter, and subterminal raindrops become dominant above 0.5 mm in diameter. The dominance of superterminal raindrops in smaller diameter range shows that these are the broken fragments of a few large raindrops due to breakup processes. These small fragments pursue the velocity of parent drop and fall faster than expected (Montero-Martínez et al., 2009). Subterminal raindrops show its dominance above 0.5 mm, fall slower than expected terminal velocity, can be due to the impact of turbulence, drop oscillations for large drops, etc. (Montero-Martínez et al., 2009).

4.5. Superterminal and Subterminal Velocity Relation With Raindrops Shape (Axis Ratio)

The equilibrium shape of a raindrop is decided by the balance of forces such as surface tension, hydrostatic pressure, and aerodynamic pressure due to airflow around the drop. Raindrop shape can be defined in terms of axis ratio \( \frac{b}{a} \) between vertical \( b \) and horizontal axis \( a \) of the raindrop. The raindrops with an axis ratio less than 1 are oblate shaped drops and having a ratio greater than 1 are called prolate shaped drops (Pruppacher & Beard, 1970). The assessment of the variation of axis ratio for superterminal and subterminal raindrops and their respective diameter ranges are important in examining the microphysical properties of these skewed drops. Figure 11 shows the normalized distribution of the axis ratio \( \frac{b}{a} \) for superterminal and subterminal raindrops for different seasons. In all the seasons, superterminal and subterminal raindrops show a similar pattern of arrangement with a little difference among different seasons. In the premonsoon season, superterminal raindrops concentrated in smaller diameter range and subterminal raindrops are widespread over larger diameter range.
season, the drop axis ratio for subterminal raindrops is in the range from 0.1 to 1.2. The axis ratio of subterminal raindrops show a bimodal distribution with its primary peak around 0.2 and a secondary peak at 1. This shows that the subterminal raindrops are either oblate or spherical. Superterminal raindrops distribution is unimodal with axis ratio ranges from 0.7 to 1.9, maximizing at 1.1, implies most of the superterminal raindrops are prolate spheroid or spherical. Monsoon and postmonsoon season also show a similar pattern of raindrops axis ratio distribution, where ~30% of subterminal raindrops occur at 0.2 drop axis ratio, and superterminal raindrops exist its maximum at drop axis ratio of 1.1. However, in the postmonsoon season, the superterminal drops show a bimodal distribution with its primary peak at 1.1 and a secondary peak at 1.7. This indicates that most of the superterminal drops are prolate spheroids during the postmonsoon season.

From this figure, it is noticeable that most of the subterminal raindrops occur at an axis ratio less than 1, which indicates that the subterminal raindrops are oblate shaped. In oblate shape, the raindrop’s horizontal axis is higher than the vertical axis. From velocity diameter relationships, we found that subterminal raindrops have higher diameters, and hence, we can generalize that bigger size, and oblate shaped drops are the subterminal raindrops. The effect of air resistance, drop oscillations, and a large extent of collision-coalescence processes reduce their fall velocities (Montero-Martínez et al., 2009). In the case of superterminal raindrops, the major portion of the drop axis ratio is in the range from 0.9 to 1.9 and is either spherical or prolate. Hence, the superterminal raindrops are of small size and prolate spheroid shape, falling faster than expected terminal speed. This strongly suggests that these raindrops are broken fragments of few large drops formed by breakup processes (Montero-Martínez et al., 2009).

4.6. Diurnal Variations of Superterminal and Subterminal Velocity

The different seasons have distinct rainfall patterns with unique diurnal patterns. Diurnal variation of superterminal and subterminal raindrops gives an idea about these features in a particular season and entity of these drops in the rainfall pattern. Figure 12 shows the diurnal variability of superterminal and subterminal raindrops during different seasons. During premonsoon season, rainfall with superterminal and subterminal raindrops mainly occurs in the evening hours with a duration of 4–5 hr (15–19 LT). Occasionally, sometimes rain happened in midnights and early morning hours. Distribution of superterminal and subterminal raindrops during premonsoon season is almost similar for the evening rain; however, at midnight, the rains are enriched with superterminal raindrops. In the monsoon season, rain with the presence of these skewed drops occurs for the whole day, which is the unique feature of monsoon season, and its amplitude is higher in the evening hours with a dominance of subterminal raindrops. Most of the time, in monsoon, both superterminal and subterminal raindrops are equally distributed. The rainfall with superterminal and subterminal drops usually occurs during daytime and persists till late evening in the postmonsoon season. The distribution of drops is nearly equal for most of the precipitation events in subterminal and superterminal
raindrops. This shows that the superterminal and subterminal raindrops are present in the definite proportion in all the seasons, which are associated with different types of rain.

### 4.7. Possible Feedback From Organic and Bio-aerosols on Superterminal and Subterminal Raindrops

The size of raindrops depends on the collision-coalescence and breakup processes, which rely on the differences in fall velocity. Furthermore, the aerosol particles in bigger size can act as a giant cloud condensation nuclei (GCCN) that tend to produce bigger (larger) drops, can impact the coalescence processes, and can act as a rain embryo (Chen & Liu, 2004; Cheng et al., 2010; Feingold et al., 2005; Möhler et al., 2007; Teller & Levin, 2006). The larger raindrops produced by GCCN can fall faster than their fall velocity. Möhler et al. (2007) showed that the sea salt, biological particles, and mineral dust could act as GCCN. It is to note that the biological aerosols can act as both ice nuclei and GCCN, and thus, their effect could be very important in cloud and rain processes. The study site, WGs, is rich in vegetation and thus acts as a source for organic and biological aerosols (e.g., pollen, lichen, bacteria, and leaf fragments) (Anil Kumar et al., 2016). Thus, the presence of GCCN like sea salt along with other organic and biological aerosols are more effective in modifying the intensity and amount of precipitation in clouds with bigger drop size and higher terminal velocity. Hence, understanding the impact of GCCN (i.e., biological aerosols, sea salt, etc.) on the cloud development and initiation of rain formation in cloud modeling studies are important. This knowledge is important in cloud modeling studies, as it can help to emphasize the increase of precipitation by accelerating the growth of raindrops over a particular region. Therefore, this present observational study on the raindrops size and terminal velocity might be helpful for a better understanding of cloud modeling activities.

### 5. Summary

The existence of superterminal and subterminal raindrops has been investigated using 2DVD observations at Mahabaleshwar (~1.4 km AMSL) in the WGs, India, during the period from 2012 to 2015. Superterminal and subterminal raindrops are classified by 30% positive and negative deviations, respectively, in their observed fall velocity from calculated terminal velocity using the criteria mentioned by Montero-Martínez et al. (2009). The analysis was performed by considering the condition that the wind speed should be less than 2 m s$^{-1}$, and raindrop diameter should be greater than 0.5 mm and less than 2 mm (Bringi et al., 2018). The investigation was carried out over premonsoon (March–May), monsoon (June–September), and post-monsoon (October–November) seasons. Results have pointed out the presence of these subterminal and superterminal velocity skewed raindrops in all seasons. The subterminal drops dominate the superterminal drops in all the seasons. The higher updraft speeds over the WGs enhance the drop oscillations and results in smaller terminal velocities for the raindrops. The superterminal and subterminal drops are present in higher proportions during monsoon season compared to other seasons.
Further, we investigated the relationships of superterminal and subterminal raindrops with precipitation features like rain rate, raindrop diameter, and axis ratio. Superterminal and subterminal raindrops are present in almost all rain rate ranges, but the amount of these drops decreases with an increase in rain rate. However, superterminal raindrops dominate the subterminal drops in low rain rate ranges (rain rate < 5 mm hr$^{-1}$). From raindrop diameter observations, it is found that these drops exist mainly in raindrop diameter < 1 mm (Larsen et al., 2014). The superterminal drops dominate below 0.5-mm diameter, whereas the subterminal drops dominate above 0.5-mm diameter.

Axis ratio, which gives the idea about the shape of drops, illustrates that the subterminal raindrops are almost oblate shaped (axis ratio <1), and superterminal raindrops are prolate spheroid shaped (axis ratio >1). The superterminal raindrops are small, which are formed due to the breakup of larger raindrops. These raindrops fall faster than expected velocity. The subterminal raindrops are large and oblate shaped drops and fall slower due to air resistance and drop oscillations. Diurnal variations of these raindrops show their presence in all the season, however, their distribution varies.

Further, the terminal velocity of raindrops is calculated using the derived equations (Atlas et al., 1973; Gunn & Kinzer, 1949), and these velocity criteria are applied in most of the fields like numeric modeling, DSD from impact disdrometer, and erosion parameterization. From this study, it is evident that the existence of superterminal and subterminal raindrops which demands the robustness of this velocity criterion.

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