Dynamical evolution of vertical profile of rain structures observed using ground-based radar over a tropical station

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Abstract

In this study, measurements of vertical profiles of rain parameters have been made using vertically pointing micro rain radar (VPMRR) at Akure (7.30°N, 5.13°E). Rain parameter data collected over seven-month rainfall episodes during the intense rainy season (April to October) have been analyzed for a dynamical evolutionary trend over the site. Nearly all the episodes observed followed a similar pattern, hence, a single continuous rainfall episode occurring between 20:45:00 h and 21:14:00 h Greenwich Meridian Time (GMT) local time on 6th August 2018 is presented in this report. The results show no significant changes to the rain parameters (such as rain rate and liquid water content) nor contributed to the raindrop size distribution, based on average fall velocity of 6.55 m s⁻¹ and rain rates within 1.3 and 2.6 mm h⁻¹. This is to enable a stable fall for the dominant drops during the period. Further, the results revealed the transformation and collision of smaller drops to enhance a stable fall of larger drops during the rain event. The information from the study will be useful for radar meteorologists and micro-wave engineers in their designs.

1. Introduction

Precise measurement of the time-based variation of raindrop size distributions (RDSD) is one of the fundamental concerns for communication engineers and many organizations involved in the European Space Agency (ESA) and International Telecommunication Union (ITU), among others (Ojo et al., 2008). These measurements have become vital due to their critical role in understanding the hydrological cycle with relevant scientific applications in radar meteorology, microwave communication applications, satellite remote sensing, cloud physics, and propagation impairments due to rain (Barthès and Mallet, 2013). The measurements also play an important role in the verification of modeling purposes, especially in the tropical regions which comprise some features, such as the presence of large raindrops, higher frequency of rain occurrence, and high intensity of rainfall (Obiyemi et al., 2014). However, many researchers have employed different instruments like rain gauge and the Disdrometer in measuring rainfall parameters. Besides, over the last 5 decades, there has been ongoing progress in radar technology and its applications. Studies have revealed that both the ground-based weather radars and the space-borne-radar show inaccuracies on the characteristics of precipitation surfaces (Das and Maitra, 2016). These inaccuracies are mostly from the growth of raindrops, which are mostly caused by coalescence, melting, evaporation, and breakup. Also, the variation in the drop size distributions (RDSD) might have a substantial effect on the rain rate (RR) profile estimation along the vertical direction. Several studies had been carried out in the past to address this issue using radars, especially in the Tropical Rainfall Measuring Mission (TRMM) relation (Cluckie et al., 2000; Thurai et al., 2003; Peters et al., 2005). Although, utmost studies focused on using ground-based instruments to adjust the bias in the ground precipitation estimation of the radar data (Seo et al., 2000; Koistinen and Michelson, 2002; Bellon et al., 2007).

The objective of this paper considered some observations of the vertical structure of rain using vertically pointing micro rain radar MRR-2 (henceforth referred to as VPMRR) in the Ka-band frequency in Akure, Nigeria, a tropical location based on the algorithm developed by Peters et al. (2005). These observations are to comprehend the variation of drop size distribution with height in the location considered.

2. Methodology

2.1. The study location

The study location, where the data used in this study was collected is the Federal University of Technology, Akure (FUTA), Ondo State,
(7°15’N, 5°15’E) Nigeria, as shown in Figure 1. Ondo State in several places composed of lowlands, plus rugged hills with granite outcrops. Generally, the land extended from the southern coastal portion (<15 m above the sea level), through the rugged north-eastern hills. The climate of Ondo State is a lowland tropical rainforest type, with discrete dry and wet seasons. The average monthly temperature in the south is about 27 °C, with an average monthly range of about ±2 °C, whereas the average relative humidity is above 75%. However, the mean monthly temperature in its range in the northern part of the state is around 30 °C and about ±6 °C, respectively. The monthly mean of the relative humidity is slightly <70%. Also, rain falls throughout the year in the south, except in the three months from November to January, which may be moderately dry. The average annual rainfall is over 2000 mm. However, there’s a marked dry season in the north, from November through March, where there is little or no rainfall. The average annual rainfall observed in the north decreases significantly to about 1800 mm (Tomiwa et al., 2016).

2.2. VPMRR principle

The measuring principle of the VPMRR is the transmission based on a 24 GHz frequency on electromagnetic waves. The signals are released vertically upward into the atmosphere; some portion of the signal is emitted and dispersed back through the raindrops to the parabolic antenna. Then, the output signal remains continuously transmitted (that is, continuous wave, CW mode).

Due to the raindrops falling velocity on the stationary antenna, there seems to be a change in the frequencies between the received signals and the transmitted signals which is recognized as Doppler frequency. This frequency is related to the amount of the raindrops falling velocity. Since the raindrops of diverse diameters have diverse falling velocities, therefore, the backscattered of the signal consists of a diverse Doppler frequency distribution (Atlas et al. 1973). The spectral examination of the signal received produces a power spectrum with a widespread distribution line conforming to the Doppler signal frequencies. This spectrum is determined by the radar’s electronics with a time resolution of 10 s and sent to the data control and acquisition system connected to it. The drop spectrum is then computed by using the radar module (METEK, 2014).

Some correction of terms is further taken into consideration such as the integration of drop spectrum, followed by 30 s averaging and capturing of the actual rain rate and the precipitable liquid water content. The Doppler spectrum radial velocity measured by VPMMR spans from 0 to 12 m s⁻¹. The processing of the real-time standard attributes drops diameters to the Doppler velocities using the relationship provided by Atlas et al. (1973). The Mie theory is further used to analyze the number of raindrops from the reflectivity of the spectral volume. Some corrections are applied to reduce the effects of oblate raindrops, which lead the lower air densities to the higher dropping velocities at elevated altitudes. Table 1 outlines the specifications of the VPMRR.

The rainfall parameters from the VPMRR are related by the following (Peters et al., 2005; METEK, 2014):

The rain rate, RR relates with the drop size distributions as presented in equation (1) (METEK, 2014):

\[ RR = \frac{\pi}{6} \int_0^\infty N(D)D^3V(D)dD, \]  

(1)

where \( \pi/6 \ N(D)D^3 \) is the volume of the differential droplet number density, and \( V(D) \) is the terminal falling velocity (m s⁻¹).
The radar reflectivity factor, \( Z \), also relates with the drop size distributions as presented in equation (2) as cited by (Peters et al., 2005):

\[
Z = \int_0^\infty N(D)D^6dD,
\]

where \( D \) is the drop diameter (mm), \( N(D) \) denotes the rain drop size distributions (m\(^{-3}\) mm\(^{-1}\)).

The liquid water content, \( LWC \), is related by (Peters et al., 2005) as presented in equation (3):

\[
LWC = \rho_w \frac{\lambda}{2} \int_0^\infty N(D)D^3dD,
\]

where \( \rho_w \) is the density of water (kg/m\(^3\)).

The fall velocity \( v(D) \) in equation (4), is related by (Peters et al., 2005):

\[
v_D = \frac{\lambda}{2} \int \frac{fP(f)}{P(f)} df
\]

where \( f \) denotes the Doppler frequency (Hz), \( \lambda \) is the radar wavelength (m), and \( P(f) \) is the spectral power related Doppler frequency (W).

Based on the VPMRR algorithm, the backscattered cross-section needed to obtain the number of drops has been computed using the principle of Mie theory. The backscattering cross-section \( \sigma_m \) of a dielectric sphere for a plane electromagnetic wave using Mie theory is given by (Löffler-Mang et al. 1999; Harikumar et al. 2012) as represented in equation (5):

\[
\sigma_m = \frac{\lambda^2}{4\pi} \sum_{n=1}^{N} (-1)^{n+1}(2n+1)(a_n - b_n)
\]

| Parameter                  | Quantity                  |
|----------------------------|---------------------------|
| Frequency                  | 24.1 GHz                  |
| Transmit Power             | 50 mW                     |
| Transmit Operation         | Frequency modulation continuous wave |
| Beam Width                 | 2                         |
| Antenna (Transceiver)      | Offset parabolic type     |
| Height resolution          | 160–4800 m                |
| Vertical resolution        | 160 m                     |
| Temporal resolution        | 30 s                      |
| Height range               | 30 range gates            |

Table 1. VPMRR specifications.

![Figure 2](image.png)  #351

Figure 2. Rain occurrences obtained for stratiform and convective rain types for different wet season months of the year (May–October, 2018).
where $a_n$ and $b_n$ are derived from Bessel and Hankel functions (Loeffler-Mang et al. 1999; Harikumar et al. 2012).

### 2.3. Data analysis

In this study, seven-month rainfall parameters data during the wet season of the year 2018 were obtained from the Communication Physics Research Group archive data, in the Department of Physics, the Federal University of Technology, Akure (FUTA). The parameters imperative to this study from the archived data are rain rate (RR), fall velocity $v(D)$, and the number of drops (N). The vertical profile information (rain-rate) were used to characterize the RDSD into different rain types, according to stratiform ($0 \, \text{mm/h} < \text{RR} < 10 \, \text{mm/h}$) and convective rain type ($\text{RR} \geq 10 \, \text{mm/h}$) (Peters et al., 2005). Rainfall rates less than 10 mm/h can often be associated with convection (Atlas and Ulbrich, 2000), especially during its growth stage or near the leading edge of expanding or propagating convective cells.

However, due to the lack of physical measurement of the drop diameters, an estimation approach presented by Fraile et al. (2015) was adopted. It was calculated from the fall velocity $v(D)$ using equation (6) as:

$$v(D) = (9.65 - 10.3 \exp(-0.6D[\text{mm}])))dv(h),$$  \hspace{1cm} (6)

For $0.109 \leq D \leq 6 \, \text{mm}$, where $D$ is therefore expressed in equation (7) as (Fraile et al. (2015)):

$$D = \frac{1}{6} \ln \left( \frac{10.3}{9.65 - \left( \frac{\partial D}{\partial \ln h} \right)} \right).$$  \hspace{1cm} (7)

The drop size, $D$ is measured in mm, while the fall velocity, $v(D)$, is in m s$^{-1}$.

The terminal fall velocity height dependence on correction factor as a result of the changes in the air density, $dv(h)$, is estimated based on the polynomial of the 2nd order as in equation (8) (Foote and Du Toit, 1969):

$$dv(h) = \left[ 1 + 3.68 \times 10^{-5}h + 1.71 \times 10^{-7}h^2 \right]$$  \hspace{1cm} (8)

An overestimation measurement might occur at around the zero-degree isotherm height due to the change in phase of water as reported by Harikumar et al. (2012). It was also reported over the location of this study in the work of Ojo et al. (2014), with the use of a satellite radar measurement, that the zero-degree isotherm height is above 4600 m. Basically, attenuation occurs due to the Mie scattering processes at Ka band and especially during convective events. Hence, the analysis of this work is limited to 3200 m height to avoid this overestimation. Also, there are chances of electromagnetic radiation attenuation, at higher altitudes during higher RR. However, an attenuation correction is performed by the VPMRR algorithm on the moderately high rain rates by calculating Mie extinction from the derived RDSD (METEK, 2014). Also, the influences of turbulence conditions and vertical wind that may arise from VPMRR observations are neglected, since they may cause some errors for the individual RDSDs and the associated rain parameters. Convective motions (i.e., upward velocity $>2$ m/s), as defined by Houze (1981) will increase the Doppler shift, and thereby causing an incorrect retrieval of the RDSD and subsequent rainfall parameters. In this study, we removed the data due to this effect to provide reliable results. Since the objective of this study is to consider the vertical observation of some rain structure in a tropical location, hence, this work uses the data analysis of a single precipitation event.
3. Results and discussion

3.1. Monthly occurrence of RDSD based on rain type

Figure 2 presents the monthly occurrences of RDSD based on rain types during the intense rainy period (April to October, AMJJASO). A rainfall event typically denotes a specific rainfall depth distributed in time according to a specific temporal rainfall distribution. Generally, the stratiform rain type contributed more to the rain occurrences during the period of observation, covering about 75% of the event. Although, this is not as intense as observed in June, while the highest occurrence of the rain events for stratiform rain type was recorded in August, specifically on the 6th day. Also, the highest occurrence of the convective rain type recorded occurred in the month of June on the 18th of the month. Time series analysis of the peak occurrence of rain events can be used to generate rain attenuation for microwave link applications, especially if the radar is located in the middle of the microwave link.

3.2. Vertical profiles and temporal trend of RR, v(D), LWC and Z

A single precipitation event with the major occurrence of rain events obtained from one day is shown in this sub-section. As earlier presented in Figure 2, the month of August recorded the highest rain occurrence on the 6th day of the month. The selected times of the profiles were chosen because it signifies the period with more rain occurrence. It is to be noted that only the stratiform rain type was considered for this study, because

Figure 4. Variation of the number of drops (m⁻³ mm⁻¹) with altitude for diverse classes of drop diameter on 6 August 2014 at (a) 20:45:00 h LT (b) 21:02:00 h LT; (c) 21:08:00 h LT; (d) 21:14:00 h LT.
of its major occurrence in the data set of the wet months. The result of rain parameters during the intense rain on the 6th of August is presented in Figure 3, together with its average variation (thick line). Generally, it was observed that RR increases as the height decreases up to about 600 m, and thereafter started decreasing with height and attains a constant trend at about 160 m. We also noted that the second profile is taken 17 min after the first, whereas the third and fourth profiles are every 6 min, showing that it took 17 min for the flux of rain in convective rain type to transform to the stratiform rain type while the subsequent profiles indicate steady falls as convective rain types. For example, in Figure 3(a), the RR profiles show the maximum rain rate occurring at about 600 m. Figure 3(b) also presents the variation of \( v(D) \) with its height for different intervals of time. We observed that \( v(D) \) was constant at different times and different altitudes. Also, the \( v(D) \) varies between 4.79 and 6.99 m s\(^{-1} \) with an average speed of about 5.89 m s\(^{-1} \), which indicates that the time taken for the drops from the top of 3200 m to reach the ground is about 540 s for this region. As seen in Figure 3(c), where the LWC is shown, a slight or no-variation was observed at all times for the height between 1000 m and 2000 m with a negative gradient. However, a positive gradient was observed at a lower height up to about 600 m, with distinct values at different times. The positive gradient behavior of the observed LWC might be due to the evaporation factor, which can be substantial at lower heights and lowest rain rates, and this changes the RDSD, which mostly affects the concentration of small drops and this result is in good agreement with the work of Das and Maitra (2016).

Figure 3(d) shows the Z over the all time considered; the Z-profile reveals a positive gradient to about 500 m height. The positive gradient further extended at the early hour up to 1600 m height. This observation is in line with the work of Das and Maitra (2016), where it is revealed that in very low rain conditions, a positive gradient observed for radar reflectivity profile could be due to evaporation. Since the maximum RR observed for the time considered is around 3 mm h\(^{-1} \), all drops falling might not reach the ground. This occurrence is the most prevalent in the region of the boundary layer near the ground, thus, the reflectivity of the radar reveals only a small degree of a positive gradient. Besides, the decrease in the positive gradient with time as shown in Figure 3(d) could be due to the changes in temperature with time. Since the temperature and moisture affect the evaporation rate as it can be observed on radar profiles. However, in Figure 3(b) where the \( v(D) \) is presented at all the time considered, the observed \( v(D) \) showed a negative slope at the lower height around 600 m and the height around 2300 m. This could be due to smaller drops since lower rain rates are usually accompanied by lower shallow clouds (Peters et al., 2005; Prat and Barros, 2010). Moreover, the overall decrease in average \( v(D) \) towards the ground can also be attributed to drop breakup. The increase below 600 m is interesting could be an indication of coalescence being enhanced by the introduction of shallow convective clouds. The information can be useful for radar meteorologists to deduce the average movements of the drops within the resolution volume in radar.

### 3.3. Vertical profiles and temporal evolution of RDSD

Figure 4(a) presents the logarithm of the number of drops variation, \( \log (N) \), together with its height in some size of classes. At 20:45:00 h GMT local time (LT), we observed that the \( \log (N) \) in its smallest drop size class, varies between 2 and 5.5 from the ground up to 3200 m height. Harikumar et al. (2012) had earlier observed that the smallest drop size of the class was between 2.5 and 5 at 700 m in India. We suggest that the difference in these observations might be due to the differences in the rain height between the two tropical regions. Besides, we observed that the maximum \( \log (N) \) in the drop size class is seen at about 2800 m, while the minimum is seen at about 1600 m. The largest drop size class for \( \log (N) \) varies between -3 and about 1.5 while the classes of the other drops fall in between. Figure 4(b) to 4(d) shows the vertical profile in the number of drops variation of diverse classes of drop diameter from 21:02:00 to 21:14:00 h GMT local time. For example, at 21:02:00 h GMT local time in Figure 4(b), we observed that the maximum number of drops commences at a height of about 200 m, while the minimum is observed at the height of about 2400 m. Reduction in higher values of \( \log (N) \) has been attributed to an indication of the movement of mass at a specific water content as a rainy patch as reported in the work of Harikumar et al. (2012). High \( \log (N) \) values continue to reduce in the subsequent hours as shown in Figures 4(c) and 4(d). Hence, the larger diameter drops with less concentration at the commencement of the event increase with time as the event advances, while the smaller drops reveal a tendency of decreasing with time. The tendency of coalescence is also noticed as the event progresses as a result of the lower terminal velocity of small drops, and higher terminal velocity of larger drops. This information could also be useful by radar meteorologists to deduce the average movements of the drops within the resolution volume.

### 4. Conclusions

In this study, trends in the evolution of RDSD vertical profiles have been studied based on the stratiform rain type. The month of August was considered to have the highest number of drops irrespective of the associated August-break experienced within the month. Based on the chosen event, there are no significant changes in the rain parameters (LWC and RR) that contributed to RDSD on the average fall velocity of 6.55 m s\(^{-1} \) and rain rates are between 1.3 and 2.6 mm h\(^{-1} \). This result enhances a stable fall for the dominant drops (larger drops) during the rain event as a result of the transformation and collision of smaller drops. Results from the contour plot shows that most of the larger drops diameters occur during the beginning of the event and increases with time. The larger drops collide and coalesce with the smaller drops and then absorb the smaller drops while falling. This study reveals the trends in the evolution of rain parameters with time and height. The time series rain rate distribution obtained from the VPMRR data can be used to determine the rain at the percentage of interest needed for rain-induced attenuation. This information could be useful for microwave link system planning and for estimation of the links budgeting. Information on the movement of the drops of rain and other precipitation parameters in the atmosphere as well as the tendency of coalescence of drops could also be useful by the radar meteorologists.

### Declarations

**Author contribution statement**

J.S. Ojo: Conceived and designed the experiments; Wrote the paper.

D. B. Akoma: Performed the experiments; Wrote the paper.

E.O Olurotimi: Analyzed and interpreted the data.

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### Data availability statement

Data associated with this study has been deposited at the communication research archive data bank of the Federal University of Technology Akure, Nigeria under the accession number CR123459.

### Declaration of interests statement

The authors declare no conflict of interest.

### Additional information

No additional information is available for this paper.
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