Microphysical Interpretation of rainfall parameters with Radar Reflectivity-Rain Rate Relationships in Tropical Regions

Supported by tetfund TERTIARY EDUCATION TRUST FUND

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Received: March 20, 2022 **Accepted:** June 18, 2022

Abstract: Measurements of rainfall parameters such as rain rates (R), Liquid water content (LWC), radar reflectivity (Z) and the corresponding fall velocities of drop (W) were carried out with the aid of a micro rain radar (MRR) located at the Federal University of Technology Akure (7° 15'N, 5° 15'E), South-west Nigeria. The equipment has the ability of measuring these parameters from the ground level to a certain height of about 4.8 km above the sea level, using a vertical resolution of about 0.16 km with 1 minute time integration. Estimation of rain rate with different height was done by classifying the type of precipitation to different rain types. Data for the rainy days in the years 2006 and 2008 were used for this research work. The change in the nature of rain which are classified on the amount of rain rates are also observed by the MRR. The result shows that bulk of the rain in this part of the world are stratiform and the controlled case results in the linear Z-R relation that was observed for steady and homogeneous rainfall conditions. A lot of the rainfall activities have a variable drop spectra that results in well-known power law Z-R relationship with coefficient a = 239.75 and b = 1.165. Comparing the results of the values a and b obtained across all heights with that obtained with other equipment like Disdrometer and MRR in other temperate regions shows good agreement and hence values obtained will assist in improved design and planning of terrestrial and satellite radio communication in this part of the world.

Keywords: Tropical region, convective rain, stratiform rain, micro rain radar, rain size distribution, rain rates

Introduction

Precipitation is a form of moisture that falls from the atmosphere on to the ground. It includes rainfalls, snow, sleet, glaze and hail. Rainfall is the amount of rain that falls in a location over a period of time and therefore a type of precipitation that occurs when water vapor in the atmosphere condenses into droplets that can no longer be suspended in the air. To improve on the present quality of precipitation measurement, there is the need to achieve progress in the understanding of the hydrological cycle (Peter et al, 2002).

Rain which is defined as a liquid water in form of droplets that have condensed from atmospheric water vapor and then become heavy enough to fall under gravity. It can be classified into either stratiform or convective modes of rainfall and are important in tropical areas where precipitating clouds are organized into mesoscale systems which contain two different environments (Houze, 2005). In the convective environment, cloud droplets are formed in narrow updrafts by the warm-rain processes of nucleation, condensation, and coalescence which provides the major source of water for raindrops through continuation of the coalescence process. The microphysical processes such as (freezing and riming) occur when the updrafts carry liquid hydrometeors well above the freezing level, while vapor deposition and aggregation are the dominant ice-phase mechanisms of growth.

Precipitation is important in knowing the Earth's climatic conditions and also the climatic changes due to activities of human e.g. the green house effects, ozone depletion, emission of aerosol into the atmosphere .Tropical climate according to the Koppen climate classification is a non-arid climate in which all twelve months have mean temperatures of warmer than 18 degree Celsius, in tropical climates there are often only two seasons which are; wet season and dry season, the wet season may run from the high- sun half of the year which runs from April to September in the Northern Hemisphere and from October to March in the Southern Hemisphere or the low-sun half of the year which runs from October March in the Northern Hemisphere and from 3 April to September in the Southern Hemisphere. Tropical climates are typically frost- free and changes in the solar angle are small, in tropical climates the temperature remains relatively constant i.e. hot throughout the year, sunlight is more intense there.

The rain drop size distribution or granulometry of rain is the distribution of the number of raindrops according to their diameter. Raindrops contains size-dependent shape which cannot be characterized by a single length. Where it falls freely in stagnant air, it tends to flattens on the bottom and spread laterally and remains rounded on the top surface (Edwin, 1999).There are three processes that accounts for the formation of drops and collisions between sizes. According to the time spent in the cloud, the vertical movement in it and the ambient temperature, the drops that have a very varied history and a distribution of diameters from a few micrometers to a few millimeters (Yong Chen *et al.*, 2019).

Raindrop size and fall velocity are part of parameters of rainfall which are been measured to check the variation, level, amount and certain height of rainfall, Raindrop size distributions are one of the important characteristics of rainfall microphysical processes. Rain drop size does not only varies among climate and tropical region but also with height, precipitation and raindrop size distribution vary across seasons and rain types. The knowledge about raindrop size distribution is useful in realizing rain integral parameters and in understanding of precipitation microphysics, rain size distribution characteristics were found to vary with rainfall type, geographical location, storm to storm, within a storm and season to season (Tokay and Short, 1996). Several instruments used in observing the drop size distribution in which each has their advantages and disadvantages. Ground-based measurements of the drop size distribution are provided by disdrometers, particle size and velocity which are the most common and cost-effective instruments.

Due to radar beam divergence mostly in long wavelength radars, the horizontal wind component and turbulence measured drop size distribution profiles suffer from measurement errors. Some Doppler radars can simultaneously measure echoes from precipitation and the ambient atmosphere and retrieve drop size distribution profiles, corrected for the effects of the vertical wind velocity and turbulence (Wakasugi, K *et al.*, 1986). However, they are liable to errors due to the leakage of the horizontal component into the vertical component and the masking of the air echo spectrum by the broadened precipitation spectrum making it difficult to observe the drop size during torrential rainfall.

The purpose of this study is to measure rainfall parameters such as rain rates (R), liquid water content (LWC), radar reflectivity (Z) and the corresponding falling velocity (W), and to analyze the variations of this parameters with time in a tropical region. It also study the absolute distribution of rain rate for each during stratiform and convective rainfall. This work covers rainfall parameters in the year 2006 and 2008 using a micro rain radar located at the Federal university of technology Akure, where values of rain rates, liquid water content, and fall velocity etc. were analyzed.

Mathematical definition of terms and Methodology

This research work is to further elaborate on the study of the relationship between radar reflectivity factor (Z) and rain rate R

$$Z = aR^b \quad (1)$$

The multiplicative factor a and the exponent b in Z-R relationship to microphysical parameters is given by;

$$N(D) = N_0 D^{\mu} \exp(-\wedge D) \quad (2)$$

D(mm) is the drop diameter, N_0 ($m^{-3}mm^{-(1+\mu)}$) is the intercept, Λ (mm^{-1}) the slope coefficient and μ is the distribution shape factor Matthias et al (2003).

Radar reflectivity (Z): Z is the radar reflectivity factor line for all the heights from 160 – 4800m above the radar. It is recorded in dBZ. It can also be calculated according to following the works of (Peter *et al.,* 2002, 2006 and Clemens *et al.,* 2006) and that of Das *et. al.,* (2010), the integral parameters from the DSD are expressed for each of the rain microstructures as:

$$Z = \int_0^{\infty} N(D) D^6 dD \quad (3)$$

and

$$R = \frac{6\pi}{10^4} \int_0^{\infty} N(D) D^3 v(D) dD \quad (4)$$

While,

Liquid water content (LWC) – These is the liquid water content of drops at various heights above the radar.

$$LWC = \frac{\pi}{6} \rho_w \int_0^{\infty} D^3 n(D) dD \quad (5)$$

Fall velocity (w): These values are the characteristic fall velocities of drops. This is the velocity of drops which deliver the maximum contribution to the total rain rate. The width of the velocity bin can be derived from the maximum number of height steps, the sampling rate and the wavelength of the radar signal. Mean fall velocity is given by:

$$w = \frac{\lambda / 2 \int_0^{\infty} \eta(f) f df}{\int_0^{\infty} \eta(f) df} \quad (6)$$

Materials and Methodology

Figure 1 shows the location of the study site at The Federal University of Technology Akure, in Akure south Local Government area of Ondo state, Nigeria (7º15`N, 5º15`E). The measurements were taken for a period of four (4) years and some selected days where rain events was much was used for this analysis.

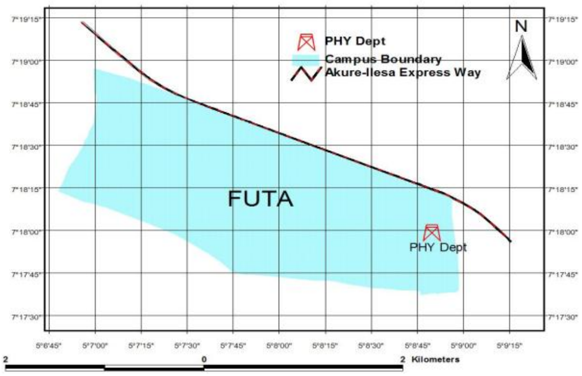

Figure 1: Map of Radar location where the measurements were taken.

According to Das *et. al*., (2010), the spectral volume reflectivity $\eta(f)$ received by the radar with depth ∂r is given by:

$$\eta(r, f) df = p(r, f) df . c \frac{r^2}{\partial r} t^{-1}(r) \quad (7)$$

Where *p(r,f)* is the spectral power, f is the Doppler frequency in Hz. C is the radar constant. The DSD is calculated from the volume reflectivity $\eta(D)$ related thus:

$$N(D) = \frac{\eta(D)}{\sigma D} \quad (8)$$

N(D) is the number of drops with size D to D + ΔD in m/s.

The mean fall velocity (V_m) is given by:

$$V_m = \frac{\lambda}{2} \frac{\int_0^{\infty} f . P(f) df}{\int_0^{\infty} P(f) df} \quad (9)$$

P(f) is the spectral power related to Doppler frequency λ is the wavelength.

Instrumentation

The Micro rain radar machine was the major equipment used in the Research work to obtain the values of some data used e.g. the Rain rate (RR), Radar reflectivity (Z), Liquid water content (LWC) etc. . Is a vertical pointing microwave profiler for measuring rain rate, liquid water content, and drop size distribution from near to several hundred meters?

The micro rain radar

This is a vertical pointing microwave profiler which is used in measuring rain rate, liquid water content and drop size distribution from near ground to several hundred meters.

Figure 2: Outdoor and indoor components of a micro rain radar

Table 1: sample data

MRR	**6.09E+10**	**UTC+02**	**AVE**	**60**	**STP**
Z	38.7	34	27.4	25.6	24.2
RR	11.23	4.19	1.4	0.93	0.82
LWC	0.54	0.21	0.1	0.08	0.07
W	7.06	6.54	6.29	6.55	6.03
MRR	6.09E+10	UTC+02	AVE	60	STP
Z	39.9	35.9	27.4	24.5	25.7
RR	14.25	5.98	1.84	1.05	1.4
LWC	0.67	0.27	0.14	0.09	0.13
W	6.99	6.76	5.8	5.71	5.89
MRR	6.09E+10	UTC+02	AVE	60	STP
Z	40	37.4	34.4	32	29.5
RR	15.67	7.89	5.23	4.45	3.89
LWC	0.75	0.38	0.33	0.32	0.31
W	6.86	6.93	6.55	6.03	5.45
MRR	6.09E+10	UTC+02	AVE	60	STP
Z	47.5	40.9	41.9	36.9	34.3
RR	40.67	10.46	14.45	9.36	7.1
LWC	2	0.46	0.83	0.71	0.64
W	8.3	8.09	7.98	7	6.75
MRR	6.09E+10	UTC+02	AVE	60	STP
Z		45.2	44.5	43.3	39.6
RR	35.53	22.02	18.81	20.55	12.42
LWC	1.75	1.07	0.86	1.46	0.94
W	7.81	8.13	8.57	8.69	8.31
MRR	6.09E+10	UTC+02	AVE	60	STP
Z	45.2	44.6	43.3	43.9	42
RR	30.41	19.02	14.19	15.37	13.91
LWC	1.48	0.88	1	0.55	0.38

Table 2: summary table of showing the raw data for 3 minutes readings for day 1 (01/09/2006)

MRR	1.41E+11	UTC+01	AVE	60	STP	160	SMP	1.25E+05	NF0
H	160	320	480	640	800	960	1120	1280	1440
Z	13.8	16.3	15.2	10.8	11.4	9.4	8.5	6.9	4.1
RR	0.36	1.14	0.64	0	0	0	0	0	0
LWC	0.06	0.23	0.14	0	0	0	0	0	0
W	2.3	1.86	1.64	1.25	2.64	2.14	2.14	1.68	2.3
MRR	1.41E+11	UTC+01	AVE	60	STP	160	SMP	1.25E+05	NF0
Z	14	16.4	13.8	10.2	8.6	8	9.5	8.2	6.3
RR	0.37	0.69	0	0	0	0	0	0	0
LWC	0.06	0.13	0	0	0	0	0	0	0
W	2.35	1.8	1.57	1.3	1.81	3.08	2.17	2.61	2.35
MRR	1.41E+11	UTC+01	AVE	60	STP	160	SMP	1.25E+05	NF0
Z	16.4	17.6	16.6	14.5	11.8	9.1	9.1	8.8	7.3
RR	0.85	1.51	1.06	0.58	0	0	0.06	0	0
LWC	0.12	0.25	0.2	0.13	0	0	0.01	0	0
W	2.81	2.41	1.92	1.47	2.12	2.34	3.07	1.95	3.64

Table 3: Sample of analyzed for the date 14/09/08

MRR	Z	RR	W	LWC
60904173400	38.7	11.23	7.06	0.54
UTC+02	34	4.19	6.54	0.21
AVE	27.4	1.4	6.29	0.1
60	25.6	0.93	6.55	0.08
STP	24.2	0.82	6.03	0.07
160	24.9	1.12	5.68	0.07
ASL	25.8	2.14	5.27	0.17
360	25.5	4.07	4.05	0.46
SMP	23.9	4.03	3.43	0.53
1.25E+05	22	2.29	3.57	0.26
NF0	21	1.51	3.86	0.14
1	19.8	1.12	4.14	0.12
NF1	17	0.82	4.3	0.15
0	13.4	0.16	3.51	0.02
SVS	11.4	0.05	3.68	0
60904173500	39.9	14.25	6.99	0.67
UTC+02	35.9	5.98	6.76	0.27
AVE	27.4	1.84	5.8	0.14
60	24.5	1.05	5.71	0.09
STP	25.7	1.4	5.89	0.13
160	27.5	2.16	5.77	0.17
ASL	28	3.32	5.4	0.3
360	27.8	4.74	4.76	0.48
SMP	26.8	6.43	3.91	0.8
1.25E+05	24.7	6.95	2.91	1.09
NF0	21.6	4	2.74	0.69

Results

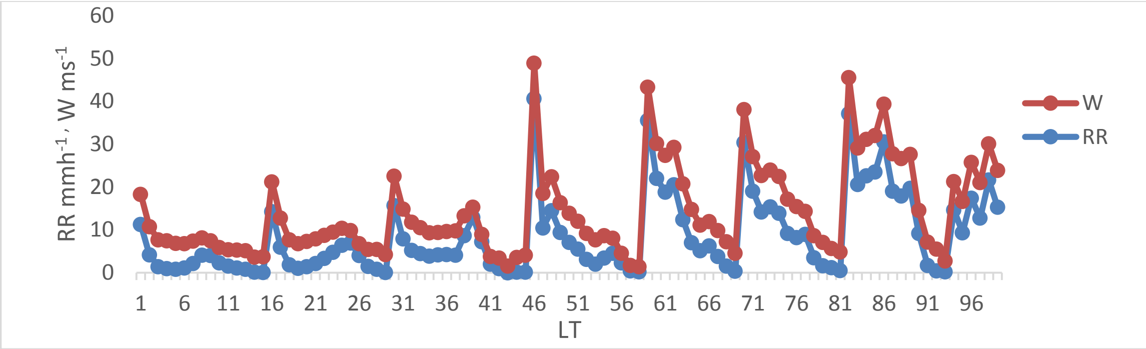

Figure 3: Rain rate, fall velocity against Time for day 14/09/06

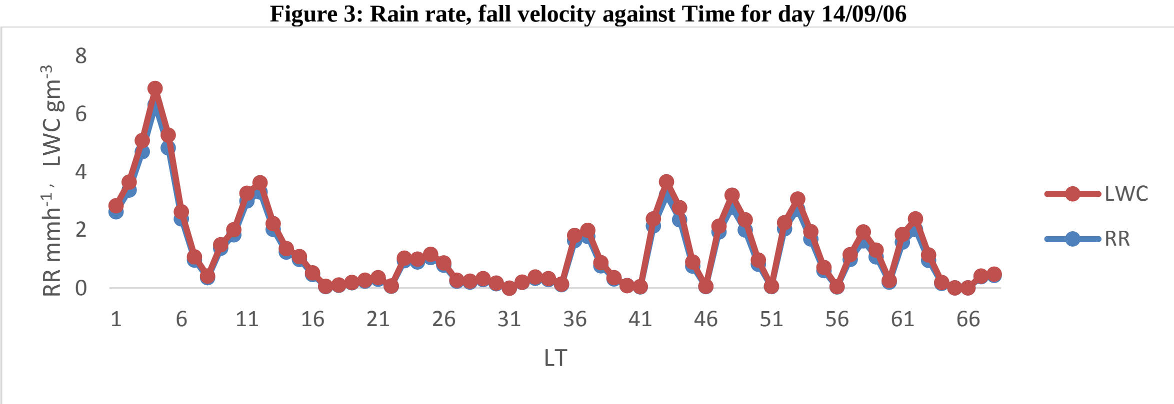

Figure 4: Rain rate, Liquid water content against Time for 15/09/06

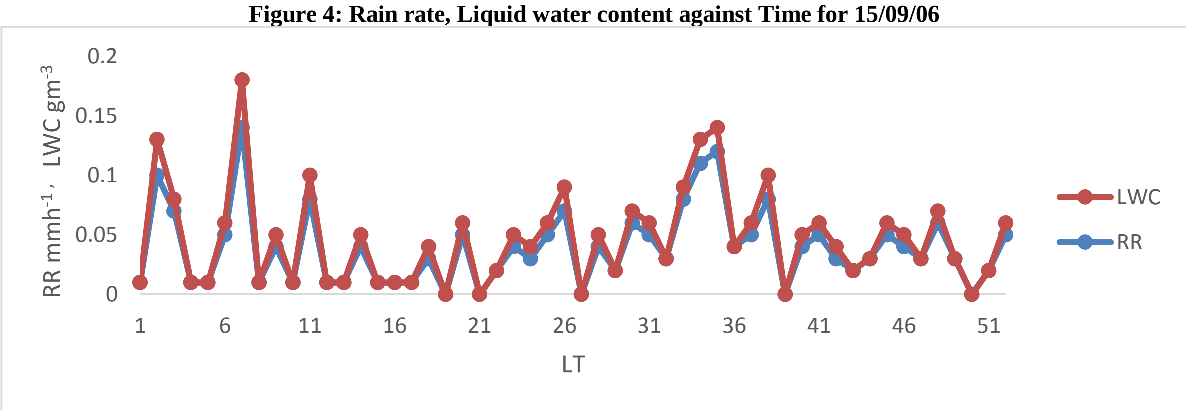

Figure 5: Rain rate, Liquid water content against Time for 06/09/06

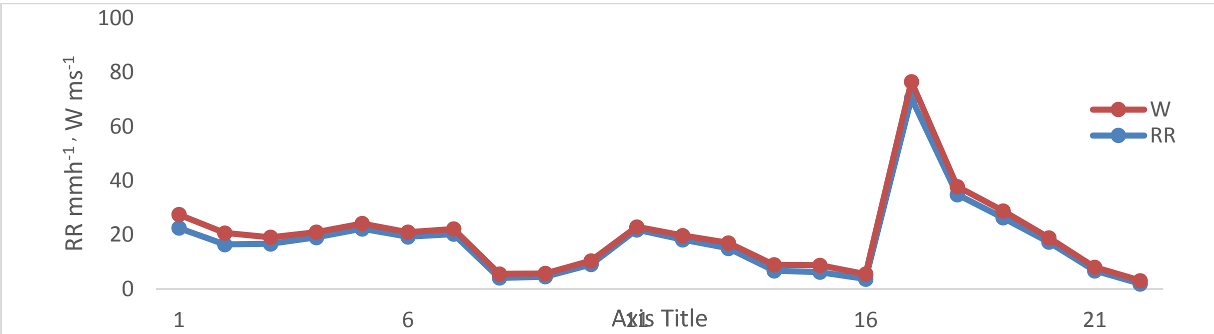

Figure 6: Plot of Rain rate, fall velocity against Time for 19/09/06

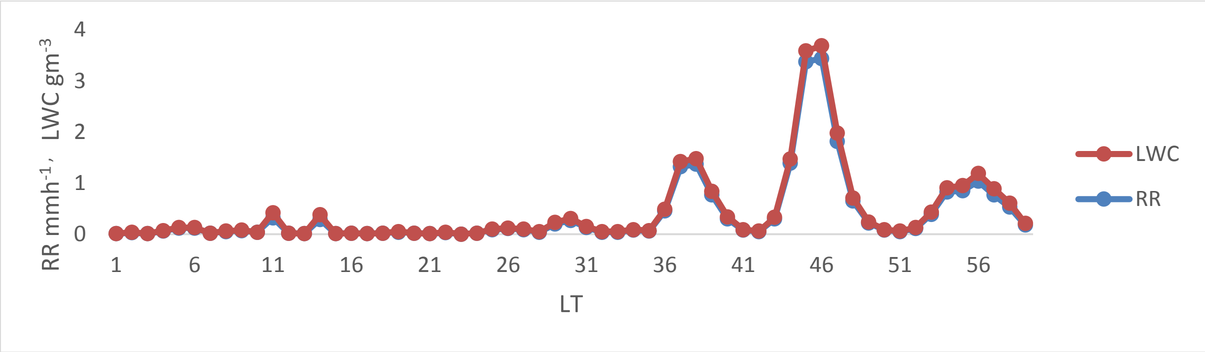

Figure 7: Rain rate, Liquid water content against Time for 10/09/06

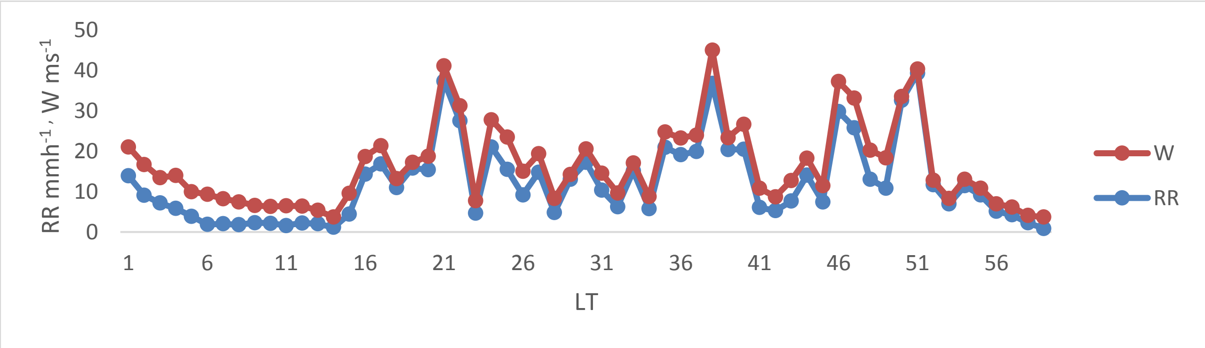

Figure 8: Rain rate, fall velocity against Time for 15/09/06

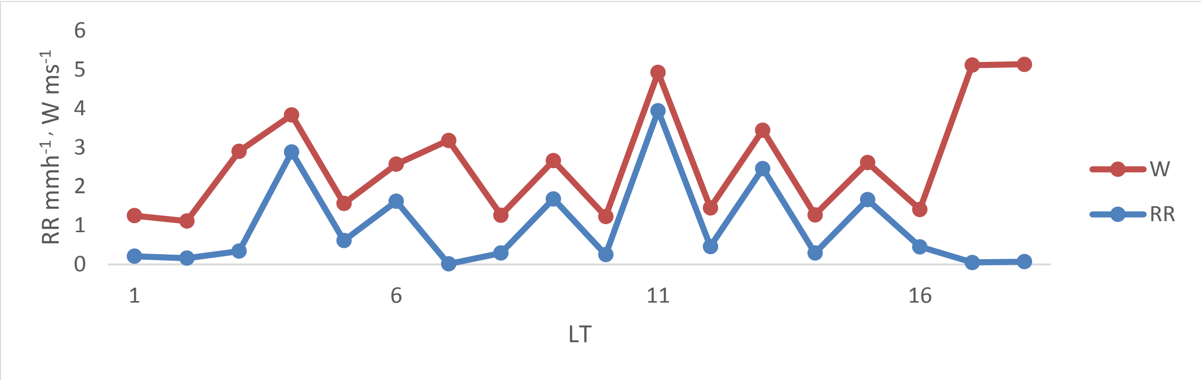

Figure 9: Rain rate, fall velocity against Time for 29/09/06

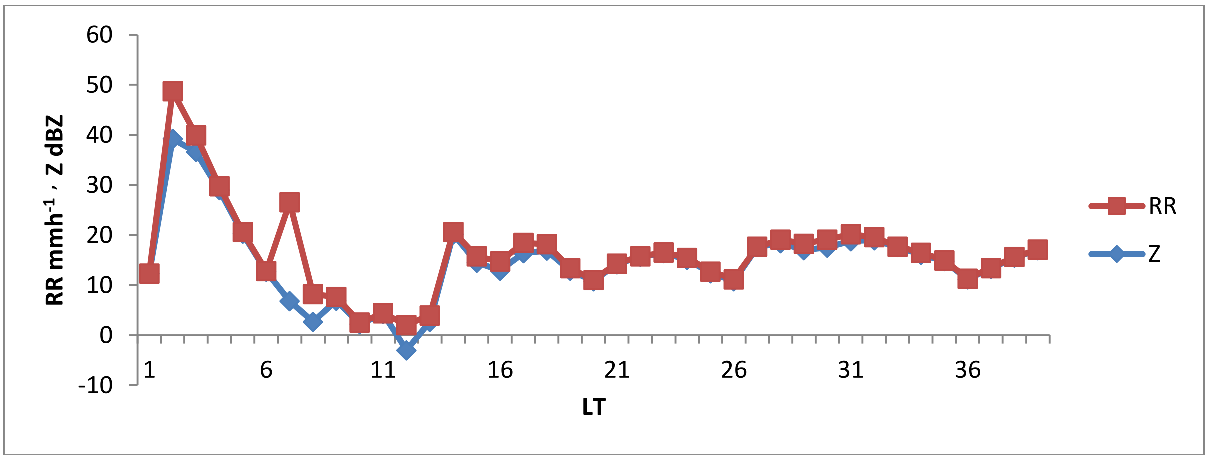

Figure 10: Radar reflectivity, Rain rate against time for 15/08/2008 (2)

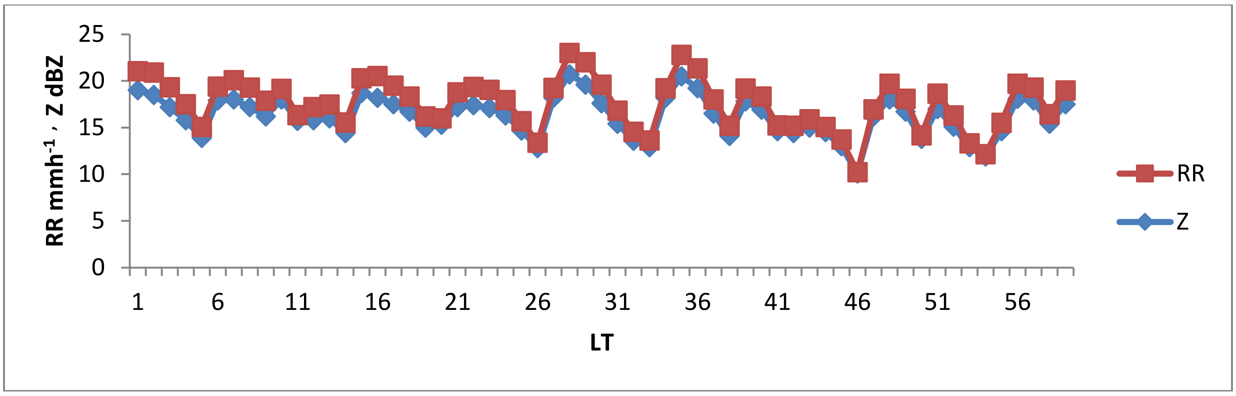

Figure 11: Radar reflectivity, Rain rate against time for 22/08/2008

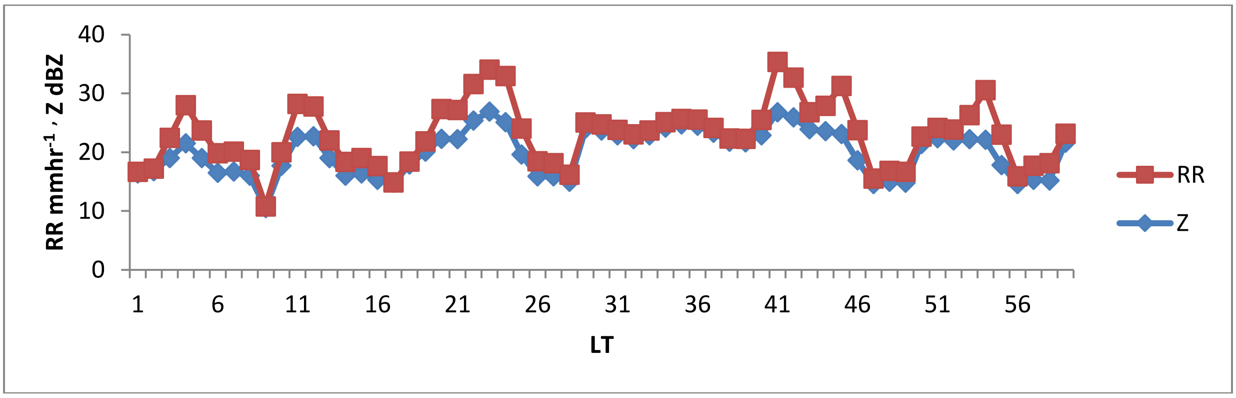

Figure 12: Radar reflectivity, Rain rate against time for 05/08/2008

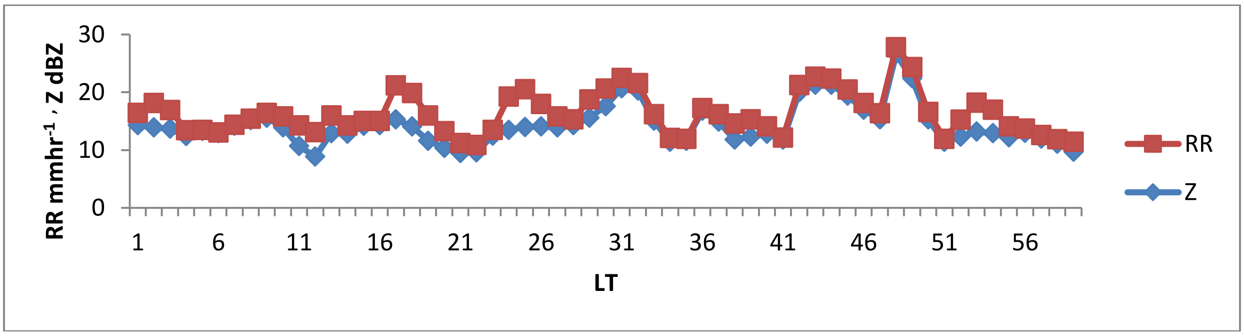

Figure 13: Radar reflectivity, Rain rate against time for 10/08/2008

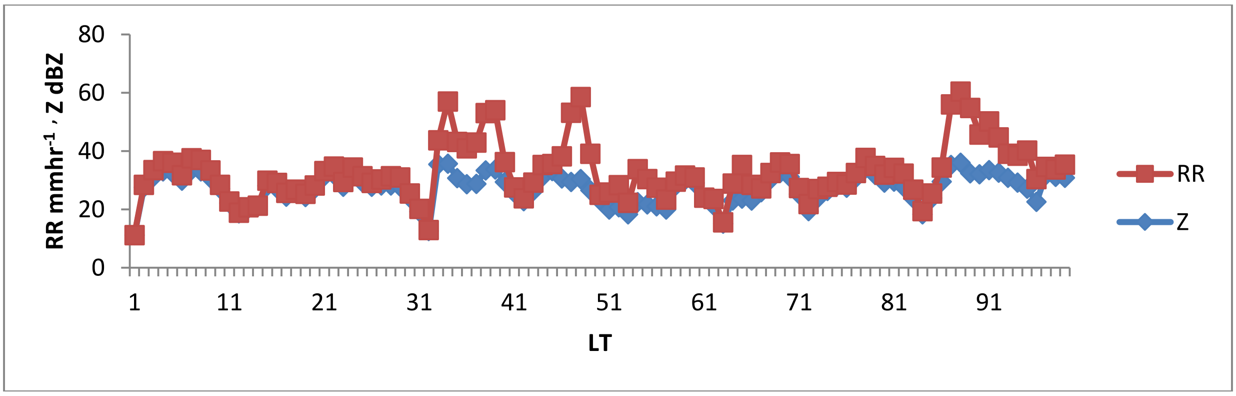

Figure 14: Radar reflectivity, Rain rate against time for 11/09/2008

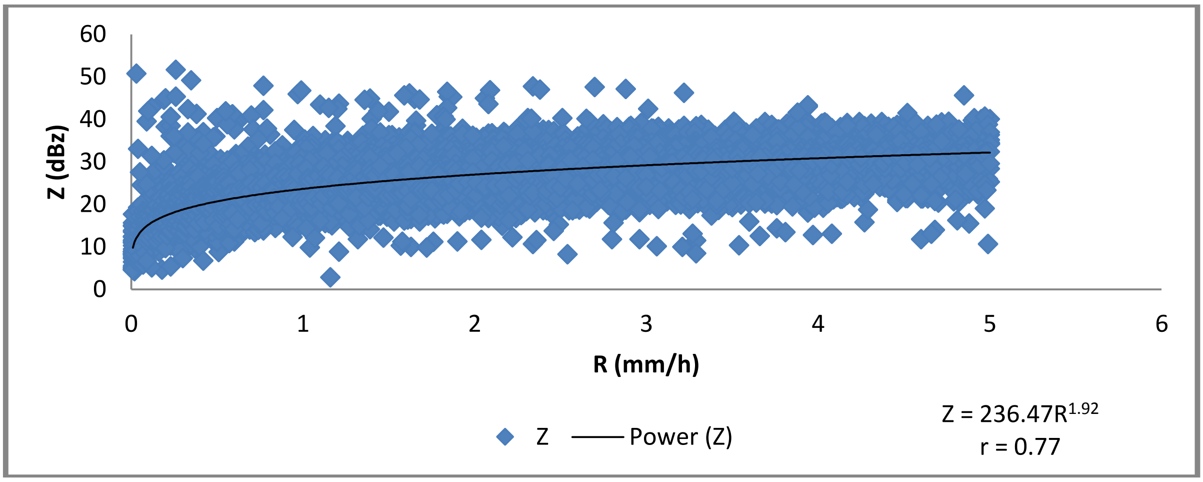

Figure 15: Z-R relation at heights 160 to 3040 m for drizzle rain type during the year 2008

Table 4: Z-R Relationships for some locations

Rain Types	**Source**	**Location**	**Z-R**
Stratiform	Joss et. al.(1970)	Locarno-mouti	$250R^{1.5}$
	Marshall and Palmer (1984)	Switzerland	$220R^{1.6}$
	Fujiwara (1965)	Miami, U.S.A	$250R^{1.48}$
	Ajayi and Owolabi (1986) **Present study** 2008	Ile-Ife, Nigeria Akure, Nigeria	$312R^{1.35}$ $239.75R^{1.165}$

Discussion

The values of rain rates, Liquid water content and the corresponding fall velocities for various height (160 m, 320 m, 480 m, 640 m, 800 m, 960 m, 1120 m) above sea levels for years 2006 and 2008 were considered in cause of the research. The results in figures 3 to 9 shows the sorted and analysed data for the relationship between the Rain rates (RR), Liquid water content (LWC) and the fall velocities (W) of data gotten from the MRR equipment using Microsoft Excel for the sorting, analyses and plotting of the graphs. Investigation of time variation of the rain event for some selected days shows that rain rates varies in same proportion with LWC and W. The amount of rain rates and fall velocity were classified into convective and stratiform in which the graphs explains and differentiate these types of rainfall (precipitation). Continuous measurements of the rain rates, radar reflectivity and falling velocity are shown in the plots above with only figures 4, 5, 7 and 9 showing purely stratiform rain and other are mixture of both convective and stratiform rain.

Figures 10 to 14 shows Radar reflectivity versus rain rate for both convective and stratiform rain at various height (160 m, 320 m and 480 m) above sea level. The changes in the coefficient of Z-R relationship for different rain event were analysed and plotted. The variation are strongly dependent on the drop size distribution. The plots shows similar variations in the rates of the drop size distribution of rain. The plots for each raining days analysed shows the three typical phases of squall lines which are convective (C), a transition zone (T) and stratiform (S) rainfall. The leading convective line (figure 14) has rain rates of about 65 mmhr-1and the corresponding radar reflectivity of 35 dBZ. The result shows an highly correlation of variation of the rainrates and radar reflectivity for all rainy days.

Figure 15 is the Z-R relationship across the heights of 0 to 4800 m above sea level for stratiform rain type in the year 2008. The coefficient a and exponent b are 236.47 and 1.92 respectively and the correlation coefficient *r* is 0.77 are all in the same range with values obtained in other temperate regions as shown in Table 4.

Conclusion

Rain events for years 2006 and 2008 obtained from a vertically pointing Micro Rain Radar were used for this research. They were classified into high (convective) and low (stratiform) intensity rains depending on the values of rain rates. From the results, it was observed that most of the rain events in this part of the world (tropical region) is the low intensity rain (stratiform) i.e. rain rates below 10 mm/hr. This is evident in the various plots of rain rate, liquid water content, radar reflectivity and the corresponding fall velocities of drop versus local time.

From the Z, R, LWC and W relations plotted against time it can be deduced that the plots follows the same pattern for all the rain types and the values of coefficient a and exponent b so obtained is in agreement with what was obtained by previous researchers in other parts of the world.

The results of this study will assist to improve design and planning of terrestrial and satellite radio communication systems in this location.

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