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VARIATION OF RAINFALL PARAMETERS WITH HEIGHT USING A MICRO RAIN RADAR WITH ONE MINUTE INTEGRATION TIME OVER TROPICAL REGION

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Abstract: The measurement of the vertical profiles of rainfall parameters such as drop size distribution, rain rate, liquid water content, fall velocity and radar reflectivity were carried out using Micro Rain Radar at Akure (Lat 5° 15'E, long 7" 15'N) in South- Western Nigeria. The vertical distributions of these parameters with heights are presented for 0 - 4800 m. The range gates for the measurement are 30 with a height step of 160 m. The variation of the drop size distribution, rain rate and liquid water content with height were evaluated. The correlation coeficient and theregression line equation was computed for each rain event. The highest rain rate and liquid water content were observed within the height range 0-6400 m. Results obtained shows a good correlation between the measured parameters, henceit shows that specific liquid water content increases with increasing rain rate for both stratiform and convective rain types in this part of the world.

Keywords: Rain drop size distribution, stratiform, micro rain Radar

Introduction

Water plays a prominent role in the atmosphere hence, It is important for the understanding of the dynamic processes in the atmosphere, weather prediction and climate research.Accurate measurement and prediction of the spatial and temporal distribution of rainfall are basic issues in communication. The measurement of various rainfall parameters have been carried out by many researchers using different instruments such as the rain gauge and the disdrometer. Raindrops are often large enough to have a size dependent shape that cannot be characterized by a single length, so there are difficulties in describing the size spectra of rain drops. The conventional solution used to describe rain spectra is in terms of the equivalent drop diameter D_o defined as the diameter of a sphere of the same volume as the deformed drop (Harikumar, 2009).

A knowledge of actual raindrop fall speeds is important in rain modelling and in estimating dropsize from areal detectors and for interpreting Doppler radar data. Raindrop fall speed is also useful in fields of research such as hydrology and soil erosion. Gunn and Kinzer (1949), Beard and Kubesh (1991), among others, have measured the terminal velocity of drops for laboratory conditions at sea level. In previous work it has been assumed that the fall speed $v_s(D)$ of a raindrop is mainly determined by its size and is the same as that for water drops falling in stagnant air. Raindrop terminal velocity v_t is the result of the balance between two opposite gravitational and drag forces acting on the drop during its vertical motion. During the formation and development of rain, a falling drop may interact with other cloud and precipitation particles, but the Gravitational effects predominate in clouds because large raindrops have larger terminal velocities, as they fall they catch-up and collide with smaller drops in their paths (Rogers *et al.*, 1989). The outcome of raindrop collision events may result in bouncing, coalescence or break up, and the knowledge of the probability of occurrence of each of these is essential for predicting the evolution of drop size distributions.

Various studies have accomplished fall-speed measurements of natural raindrops with different instruments near ground, and reported that raindrops sometimes have fall speed values different from those measured by Gunn and Kinzer (1949) which are usually used as reference for $v_t(D)$. Guillermo *et al.* (2009) reported fall speed deviations of small raindrops from $v_t(D)$ and purposed drop break up as a very reasonable explanation for their observations but they did not discard other hypotheses, such as turbulence produced by air motions. Each particle (surrounded by water) becomes a tiny droplet between 0.0001 and 0.005 centimetre in diameter. The particles range in size; therefore, the droplets range in size. However, we can call the growing droplet a raindrop as soon as it reaches the size of 0.5 mm in diameter or bigger (Diederich, 2004).

Materials and Methods

The micro rain radar (MRR)

The micro rain radar is a Doppler radar which makes use of the Doppler Effect to produce velocity data about objects at a distance. It does this by beaming a microwave signal towards a desired target and listening for its reflection, then analyzing how the frequency of the returned signal has been altered by the object's motion. With rainfall measurements making their importance felt, rain drop size distribution (DSD) has become another important parameter. In calibrating the radar and also for understanding the attenuation and other effects of rainfall on communication, knowledge of DSD has become very essential. With satellite measurements of rainfall becoming a reality, measurements of rain rate and DSD at the surface to serve as ground truth for satellite data have gained importance and accurate rain rate estimation requires detailed knowledge of rain DSD (Tokay *et al.*, 1995).

The transmitter emits radio waves that are reflected by the targets and detected by a receiver. Due to the fact that returned radio signal are usually weak, radio signals are easily amplified. Hence, radar can detect objects at ranges where other emissions like sound or visible light would be too weak to detect (METEK, 2005).

The Micro Rain Radar (MRR) is a vertical pointing frequency modulated continuous wave Doppler radar which sends electromagnetic (EM) waves only in one direction, Being a Frequency Modulated Continuous-Wave radar means the MRR continuously transmits EM-waves while the frequency varies (modulates).The mean frequency is 24 GHz corresponding to a wavelength of about 1.24 cm. The transmitted EM-waves are influenced by the matter in the atmosphere, mainly by rain drops, hail and snowflakes. The part of the EM-waves reflected towards the ground and can be detected by the receiver of the MRR. The reflected signal give information about the amount, speed and the size of the drops in the atmosphere (METEK, 2005). As the drops are falling in direction to the ground, we can use the Doppler Effect to determine the fall speed and other parameters like the drop size distribution, the rain rate, liquid water content and the corresponding fall velocity.

The rain radar transmit EM-waves moving at the speed of light propagating through the atmosphere and becomes reflected at time T in seconds as it impacts the obstacle. Thus, the reflection of droplets close to the MRR reaches the receiver earlier than the reflection of the droplets. According to this propagation time, we can distinguish between 30 height levels and at height resolution of 160 m. The Micro Rain Radar used for this work is located at the Federal University of Technology, Akure.

As the demand for more communication services is increasing daily and more access to higher frequencies up to super high frequency (SHF) and extremely high frequency (EHF) bands are now being proposed for satellite services. Allocation towards higher end of electromagnetic spectrum especially above 10 GHz is increasing on a daily basis, hence the need to meet the demand for higher data rate for various communication and multimedia requirements. It is therefore important to note that rain which can cause several decibels of attenuation has been identified to be a major cause of visual impairment at millimetre wave frequencies (above 10 GHz) and is the limiting factor in satellite/terrestrial link design, especially for tropical and equitorial regions which experience heavy rainfall, (Narayana *et al.*, 2007; Ajewole *et al*., 1999).

Drop size distribution

For the derivation of drop size distributions the relation between terminal fall velocity (*v*)and drop diameter (*D*)is used, which has been found empirically by Gunn and Kintzer (1949), and which has been put into an analytical form by Atlas (1973). Using a Generalized form, in which a height dependent density correction for the fall velocity d*v*(*h*) Is included.

$$N(D) = \frac{\eta(D)}{\sigma(D)} \qquad (1)$$

Where: $D = the\ drop\ diameter$;

$\sigma(D) = the\ back\ scattering\ cross\ section$l

Rain rate

The differential rain rate {*rr(D)}* is equal to the volume of the differential droplet number density $({}^{\pi}/_{6})\times$ *N(D)D³* multiplied with the terminal falling velocity *v(D)*. From this product the rain rate is obtained by integration over the drop size

$$RR = \frac{\pi}{6}\int_0^\infty N(D)D^3\,V(D)dD \qquad (2)$$

Radar reflectivity

The radar reflectivity factor of a population of liquid and spherical particles satisfying the Rayleigh approximation which considers the scattering of rain molecules smaller compared to the wavelength of the emitted microwave, and producing a signal of same power is expressed inmm^6/m^3. It does not depend on the wavelength of the radar frequency. Furthermore the radar reflectivity is the sixth moment of the rain drop size distribution. Thus, the measurement of different radar with different frequencies can be compared. Hence it can be expressed as:

$$Z = \int_0^\infty N(D)D^6 dD \qquad (3)$$

And in logarithmic form it is expressed as:

$$dBz = 10log_{10}\frac{Z}{Z_{ref}} \qquad (4)$$

Where $Z_{ref} = 1\,mm^6/m^3$

Liquid water content

The liquid water content (LWC) is the measure of the mass of the water in a cloud in a specified amount of dry air. It is typically measured per volume of air (g/m^3) or mass of air (g/kg).

It is the product of the total volume of all droplets with the density of waterρ_w, divided by the scattering volume. It is therefore proportional to the third moment of the drop size distribution:

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

The liquid water content of a cloud varies significantly depending on the type of clouds present in the atmosphere at a given location.

Fall velocity

A reasonable definition of velocity of those drops which delivers the maximum contribution to the total rain rate. To obtain the radial velocities, wind profilers uses the first moment of the Doppler spectra, or the spectra volume density.

$$W = \frac{\lambda}{2}\frac{\int_0^\infty \eta_{(f)}f df}{\int_0^\infty \eta_{(f)}df} \qquad (6)$$

It is also possible to derive on the basis of the drop size distribution, since the falling velocity depends on the drop size fore ach individual drop.

$$V_m = \frac{\int_0^\infty N(D)D^6 V_\infty(D)dD}{\int_0^\infty N(D)D^6 dD} \qquad (7)$$

$V_m = characteristic\ fallvelocity$

N(D)= the drop size distribution

When a spherical raindrop falls in still atmosphere at terminal velocity, the balance between gravity and air drag forces governing its fall will be reached. Under this condition, the terminal velocity can be theoretically estimated in accordance with following expression obtained by Gunn and Kinzer (1949);

$$V_T = \sqrt{\frac{4g(\rho_s-\rho)}{3\rho\mu}}D^{0.3} \qquad (8)$$

Where ρ andρ_s are, respectively, the air and raindrop densities, μ is atmospheric drag coefficient, g is gravity acceleration, and D is the diameter of the raindrop.

Project site

The measurement site chosen for the study is the Federal University of Technology Akure Ondo State Nigeria (7°15'N, 5°15'E) (Fig. 1).

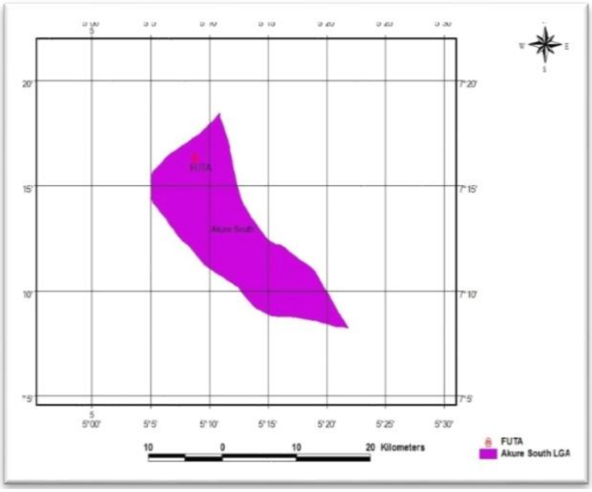

Fig. 1: Map of measuring site

Ondo State, South-Western Nigeria where this measurement was carried out is composed of lowlands and rugged hills with granitic outcrops in several places. In general, the land rises from the coastal part (less than fifteen metres above sea level) in the south, to the rugged hills of the north eastern area. The climate of Ondo State is of the Lowland Tropical Rain Forest type, with distinct wet and dry seasons. In the south, the mean monthly temperature is around 27°C, with a mean monthly range of 2°C, while mean relative humidity is over seventy five per cent. However, in the northern part of the Country, the mean monthly temperature and its range are about 30 and 6°C, respectively. The mean monthly relative humidity is less than seventy per cent. In the south, rain falls throughout the year except for the three months of November, December and January when it may be relatively dry. The mean annual total rainfall exceeds 2000 millimetres. However, in the North, there is marked dry season from November to March when little or no rain falls. The total annual rainfall in the north, therefore, drops considerably to about 1800 millimetres.

Methods

The measuring principle of the Micro Rain Radar is based on electromagnetic waves of a frequency of 24 GHz. In contrast to normal rain-radar devices, the signals are emitted vertically into the atmosphere. A part of the emitted signal is scattered back to the parabolic antenna by the rain drops. The output signal is transmitted continuously (continuous wave, CW mode in contrast to pulsed radars). The Micro Rain Radar is a Doppler radar, that is, when falling to the ground the rain drops move relatively to the antenna on the ground, which act as both transmitter and receiver.

The data were further divided into stratiform and convective rainfall, using the threshold rain rate R < 5 mm/h for stratiform rain and R> 5 mm/h for convective rain event. As Convective precipitation regions are generally identified with intermittently strong vertical velocities, high rain rates (>5 mm/hr) and small intense cells (~1-10 km horizontal dimensions). Stratiform precipitation areas are characterized by small vertical velocities, low rain rates) and wide-spread (~100-km horizontal dimension) (<5 mm/hr) as described in Joss et at., (1969). Hence the rainfall event of day 07/11 and 07/03 were stratiform in nature and that of day 07/10 was convective due to its high rain rate.

Due to the falling velocity of the rain drops relative to the stationary antenna there is a frequency deviation between the transmitted and the received signal known as Doppler frequency. This frequency is a measure of the falling velocity of the rain drops. Since rain drops of different diameter have different falling velocities (Atlas *et al*., 1973); the backscattered signal consists of a distribution of different Doppler frequencies. The spectral analysis of this signal yields a wide distribution of lines corresponding to the Doppler frequencies of the signal. The Radar electronics determines this spectrum with a high time resolution of 10 seconds and sends it to the connected control and data acquisition system, where the drop spectrum is calculated from the Doppler spectrum considering the transfer function of the radar module. The integration over the entire drop spectrum, considering further correction terms, followed by an averaging for 30 seconds, results in the actual rain rate and the liquid water content. The Micro Rain Radar measures the Doppler spectrum from 0 to 12 m/s. The standard real-time processing uses the relation given by Atlas *et al*. (1973) to attribute drop diameters to Doppler velocities. Mie theory is then used to calculate the rain drop numbers from the spectral volume reflectivity. Corrections for oblate rain drops and lower air densities leading to higher falling velocities in high altitudes are applied. Appropriate attenuation correction for moderately high rain rates is done by calculating Mie extinction from the derived DSD. Rain rate, Liquid water content LWC, and Rayleigh reflectivity Z are calculated from the DSD, while the mean falling velocity (first Doppler moment) and integral reflectivity (zeroth Doppler moment) are calculated directly from the measured Doppler spectrum. The Micro Rain Radar range resolution can be set from 10 to 200 m in 30 height intervals. Attenuation at 24 GHz prevents the use of ranges higher than 6 km.

Results and Discussion

The variation of the rain rate and liquid water content with height was evaluated for the one week data after being extracted from the raw data acquired as shown in Figs. 1, 2 and 3. These showed that the highest rain rate and liquid water content were observed along 2000-30000 m height for all cases considered. The implication of this is that along this height, we expect to have more attenuation of radio wave due to rainfall compared with the other height bins. This is because wind and hydrodynamic forces are lower at this height than higher height levels. Figs. 4-8 also shows an illustration of the variation of rain rate and liquid water content with height, and also the correlation ratio of the rain rate and the liquid water content for all the rain types.

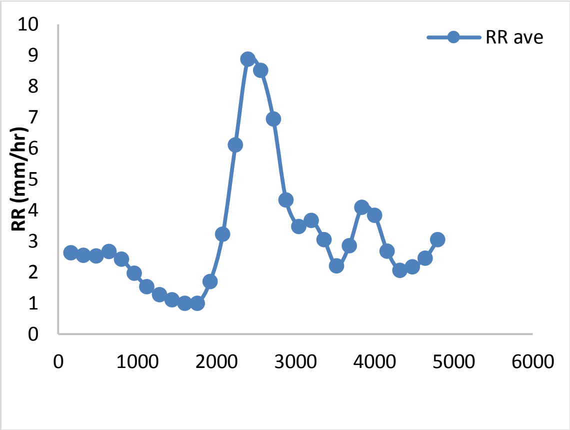

Fig. 1: Variation of Average Rain rate with height for July, 2009

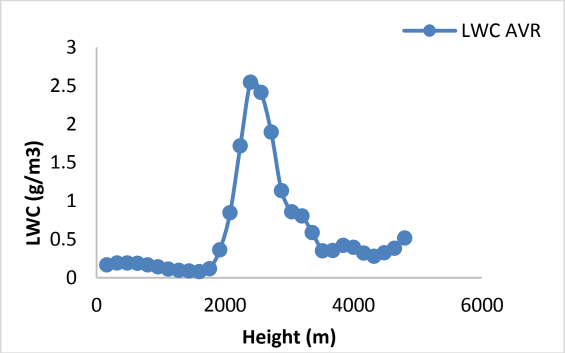

Fig. 2: Variation of Average Liquid water content with height for July, 2009

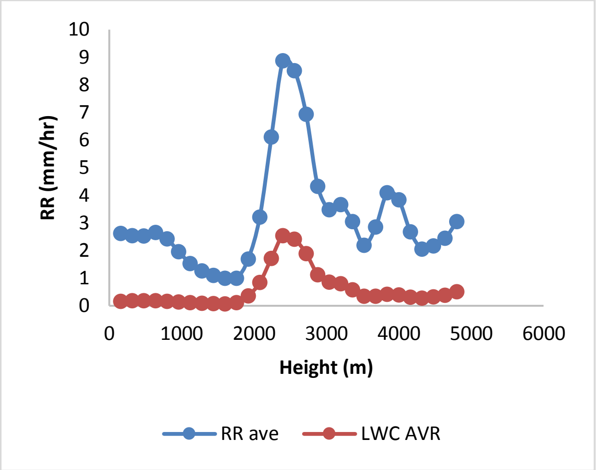

Fig. 3: Variation of Average rain rate, Average liquid water content with height for July 2009

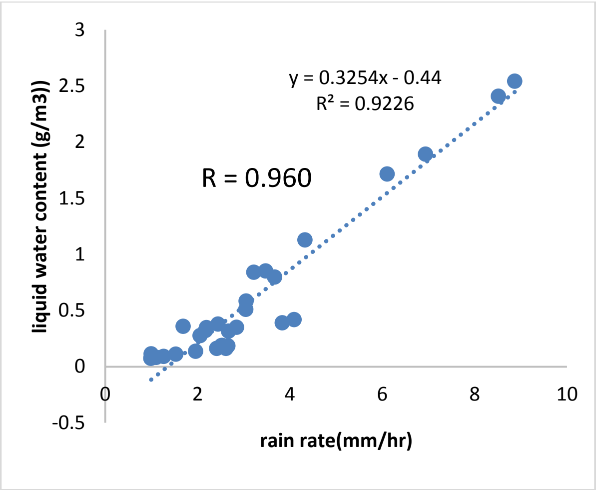

Fig. 4: Variation of Average Liquid water content with average Rain rate.

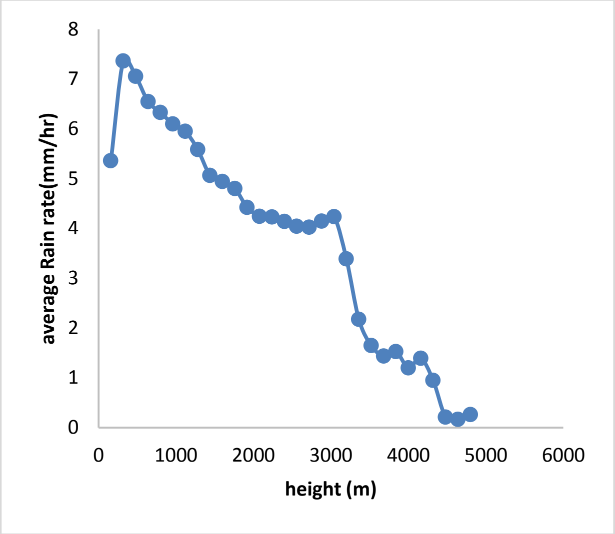

Fig. 5: Variation of Average Rain rate (mm/hr) with height for October, 2009

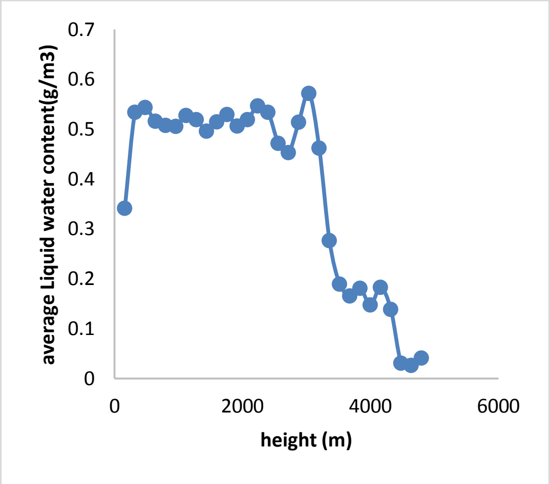

Fig. 6: Average Liquid water content (g/m3) with height for October, 2009

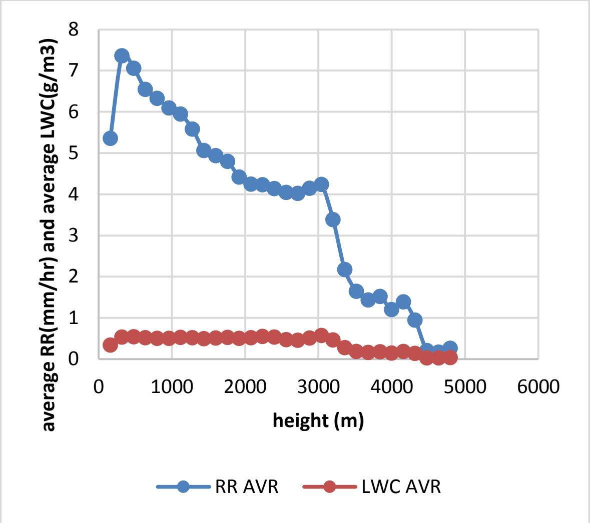

Fig. 7: Average rain rate (mm/hr) and average Liquid water content (g/m3) against height (m)

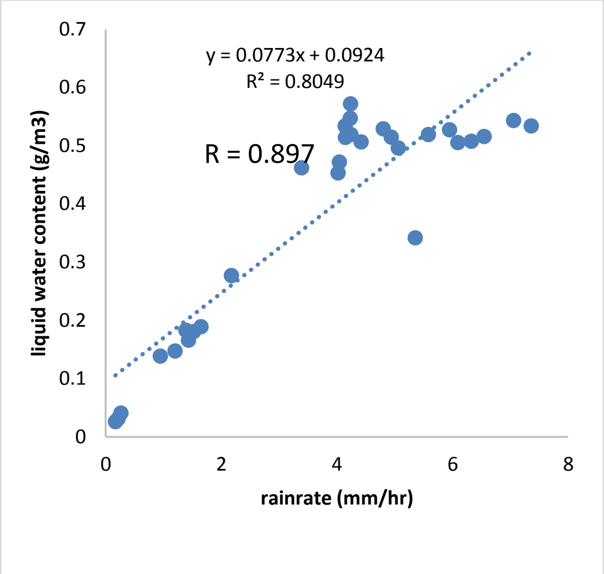

Fig. 8: Average Liquid water content (g/m3) against average Rain rate (mm/hr)

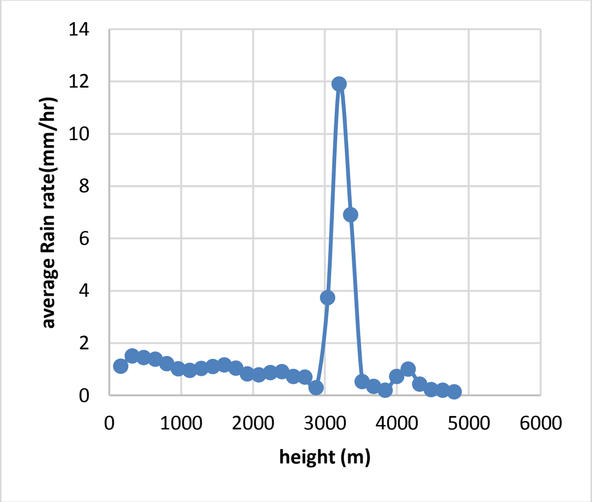

Fig 9: Graph of average rain rate (mm/hr) against height (m)

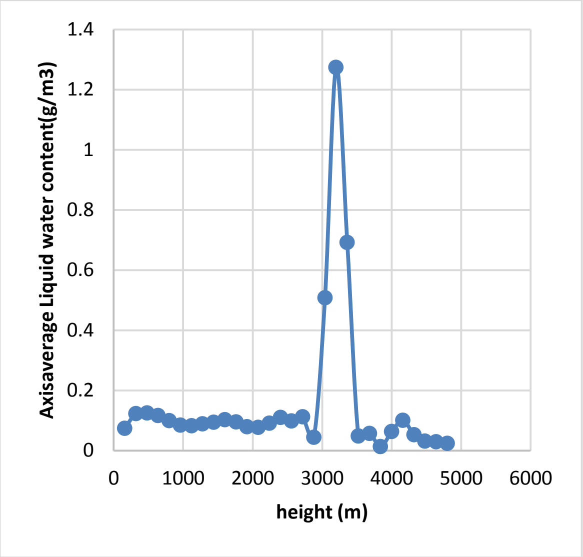

Fig 10: Graph of average Liquid water content (g/m3) against eight (m)

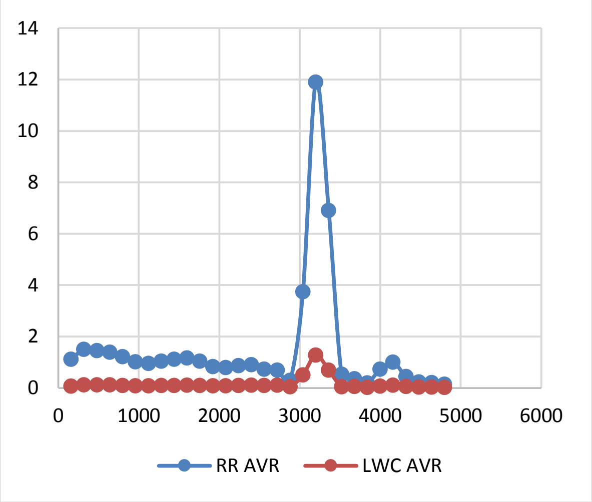

Fig. 11: Average RR(mm/hr) and average LWC(g/m3) against height(m)

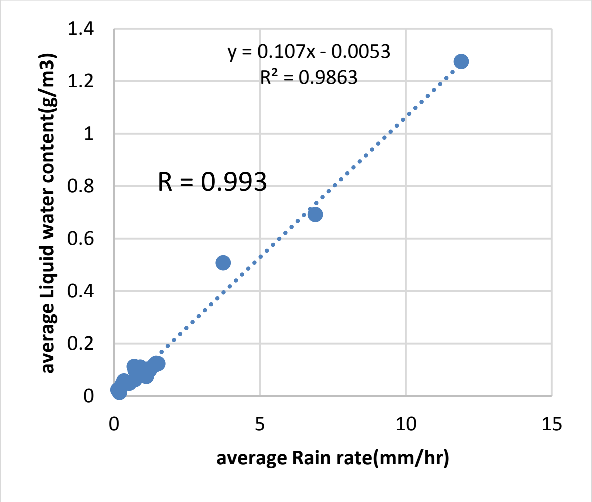

Fig 12: Average Liquid water content (g/m3) against average Rain rate (mm/hr)

The above are the scattered diagrams indicating the correlation coefficient and the regression line for the rain rate and the liquid water content for the various daily average precipitations in the year 2010. There is a high degree of correlation in all cases considered, the coefficients of correlation are better than 0.91 for most of the rain types. The power relationships obtained were comparable for all the rain types.

The rainfall parameters measured for the one week considered have been analyzed for a tropical station, Akure in Nigeria. It was also observed that the rain rate below 5 mm/hr contributed the most to the rain event in the height range 0-4800 m. Hence stratiform rainfall was observed for two days (07/03 & 07/11) of painstaking observation and data acquisition, while the height range of 0-6400 m recorded the highest rain rate. The rainfall event on 07/10 was observed to be convectional having rainfall rate above 5 mm/hr for most of the observed and recorded data. Empirical relations have been obtained among the rainfall rate, and liquid water content for the rain types using the least square power law regression. The recorded rainfall rates were classified using the criteria described in Joss *et al*. (1968), for Stratiform rain fall rate R < 5 mm/h and convective rain R > 5 mm/h.

Conclusion

To determine the variation of rainfall parameters with height using Micro Rain Radar, the recorded rainfall rates were categorized into two classes using the criteria of Nzeukou *et al*. (2002), namely, for stratiform rain rate, R<10 mm/h and for convective rain R≥10 mm/h. The rainfall rate and the liquid water content with heights were as shown in Figs. 4-12 it can be seen that stratiform rain dominate the event with a longer duration and most of the rain occurring in the night time.

The rainfall rate and the liquid water content as a function of height was shown in Figs. 4 – 12. It can be noticed that convective cells produced rain rates well above 10 mm/hr only for short duration for all the rainfall types. Examples are at the heights of 3200 m for Figs. 9 and 11.

The correlation coefficients and graphs of rain rate, the liquid water content and height relationships for stratiform and convectional rainfall for the various days and height range considered were observed good; the values are above 0.92, while that of convective rainfall type is also very good with correlation coefficient more than 0.85.

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