Analysis of Vertical Profiles of Precipitable Liquid Water Content in a Tropical Climate Using Micro Rain Radar

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Abstract

In this paper, some distinctive features of the vertical profile of precipitable liquid water content (LWC) with considerable respect to rain rates (R) and radar reflectivity (Z) obtained in a tropical location are presented. Assessment of LWC allows applications in the specific area of flight icing severity, aviation safety as well as signals traversing through the atmosphere. The parameters were typically measured using vertically-pointing Micro Rain Radar (MRR) over a period of 2 years (2011-2012) at Akure, a tropical location of Nigeria. The radar scanned at every 10 seconds and integrated over one minute samples to reduce event logging error associated with the instrument. The vertical profile of the LWC typically reveals a prominent seasonal variation. However, majority of the LWC profiles has low LWC, less than 0.1 gm^{-3} while the maximum observed LWC is about 3.18 gm^{-3}. A strong like hood relation was observed between the melting layer height and the LWC, with the LWC reaches peak at the considerable height of about 4160 m which coincides precisely with the freezing height level (rain height of ~4520 m) of the study location. Good correlation was also observed between the LWC and R in most of the heights considered. The results obtained will assist system engineers to assess the level of absorption, reflection and attenuation of electromagnetic signals as a result of precipitable LWC along the transmitting paths. The novelty of the present work is in the area of linking LWC and Z as against usual relation between Z and R.

Keywords

Liquid Water Content, Micro Rain Radar, Vertical Profile, Tropical Climate, Radar Reflectivity Factor

1. Introduction

The liquid water content contained in the precipitation size drops can be estimated from the drop-size distribution, as well as the rainfall rate. The mass of water per cubic meter of air space is essential for many applications and actually is a more fundamental parameter of the distributions than the rainfall rate. A visible distinction exists between precipitable water content and cloud droplet water content, with a diameter of about 100 µm boundary between them (Tattelmann & Willis, 1989). It has been noted that very high values of precipitable water content up to about 10 gm^{-3}, and extremely high values of cloud droplet water content, are mutually exclusive and cannot coexist. This is because the collection of small cloud droplets by the precipitation droplets is effective and rapid. For the typical raindrop spectrum associated with a precipitable water content of about 10 gm^{-3}, the time to completely sweep the volume of cloud droplets is approximately 30 secs or less (Foote & Dutoit, 1969).

Consequently, the cloud water content needs to be at a certain level, or go down, as the precipitable water content increases to extreme values. The collision breakup processes, which are indeed responsible for shaping the droplet spectrum, are well developed in extreme rate distributions. The line gap between cloud droplets and precipitation drops is in the range where collision breakup is supplying droplets. Nevertheless, the sweep out is so rapid and efficient that the water contents in the cloud droplet range cannot coexist with high precipitable water contents. Therefore, values of cloud water during extreme precipitation rates are known to be considerably high (Tattelmann & Willis, 1989).

The vertical profiles of precipitation intensity and liquid water content in the context of this report are of two forms. The first one is due to the reduction in air density with altitude, the precipitation rate for a given drop-size distribution increases with altitude. In this report, profiles of precipitation rate with altitude are presented in terms of equivalent surface rate and not the actual rate. The second consideration regarding this study is by assuming that the vertical profile of water content is to be of those formed at a certain stage of development of the cloud. That is, between tropical convective clouds where warm rain processes are dominant through a deep bottom layer of the cloud based on the more preliminary observation by Tattelmann & Willis (1989).

Considering the tremendous work that has been carried out on the subject matter by some notable researchers among such are Li & Barker, (2002), Crewell & Loehnert (2003), Paul & Paul (1985), Brandau et al. (2010), Calheiros & Machado (2014) to mention but a few, it is evident that the subject of LWC studies has received much attention, mostly in the temperate region. However, most of these attentions are focused on the liquid water content due to cloud. Although, the cloud water content is associated with several applications among this will be briefly highlighted. The liquid water content of a cloud remains a vital parameter governing precipitation formation and cloud balancing. Clouds in the lower troposphere remain a key component of the hydrological cycle (water balancing)

and exert much impact on electromagnetic wave propagation. The amount of liquid water droplets, their particle size and the vertical cloud extent also characterize the scattering and absorption features of the cloud, which in return suffer an impact on the shortwave radiation budget (McFarlane et al., 2008; Gultepe & Rao, 1993; Browning, 1994; Barker & Räisänen, 2005; Brandau et al., 2010).

Having more knowledge and information about LWC profiles will also improve our understanding of processes acting to form and maintain cloud systems and may help in improving the representation of clouds in numerical models (Korolev et al., 2007). Furthermore, it is a crucial parameter that can be related to other parameters (i.e., radiative absorption, optical thickness) within General Circulation Models GCMs (Slingo & Schrecker, 1982). This can be inferred from the recently published Fifth Assessment Report (ARS) of the Intergovernmental Panel on Climate Change (IPCC), in which it is stated that "Clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget" (IPCC, 2013). This is related to the fact that "Many cloud processes (their representations) are unrealistic in current Global Climate Models, and as such their cloud response to climate change remains uncertain" (IPCC, 2013). The large uncertainty contributed by clouds requires improvements of clouds in terms of their microphysical properties in terms of fractional coverage, cloud boundaries and their microphysical properties in terms of the particle size distribution, the concentration of the cloud particles and their sizes and the amount of liquid water.

In the context of the present study, the water content is equally applicable to the system engineers whereby the knowledge of precipitable LWC plays a dominant role in the absorption, reflection and attenuating electromagnetic signal thereby resulting into bad quality of signals at the receiving end.

In the tropical region, the subject equally received some attention (Maitra & Chakraborty, 2009; Chakraborty & Maitra, 2012) mostly in Indian region. However, most of these studies established the use of radiosonde data. Direct estimates of liquid water content are only available from costly aircraft in situ measurements confining their availability to short periods and special locations. Remote sensing by ground-based microwave radiometers are increasingly used to probe the cloudy atmosphere often in synergy with other observations, to retrieve liquid water content profile (Crewell & Loehnert, 2003). Atlas (1954) and Donaldson (1955) were among the first to implement active remote sensing to study cloud liquid water content and precipitation. However, the availability of ground based radar like MRR can easily retrieve precipitable LWC based on the Doppler spectral principle. An estimate of three-dimensional LWC of a storm volume can be obtained when radars scan several elevation angles to obtain a three-dimensional volume of radar reflectivity. In this paper, the LWC is more precisely precipitable water content since it does not include cloud drops to which the radar is insensitive. Volumetric LWC derived from radar reflectivity can be useful in the initialization and validation of numerical models, and in studies utilizing aircraft in situ data. Although, the Z-LWC estimation procedure

utilizes all the sources of error associated with the estimation of R except for the vertical variation in Z since a transformation to near surface values is unrequired as the case for this study. According to Hagen & Yuter (2003), relationships between radar reflectivity and liquid water content (Z-LWC), a very effective type of parameterization, are not as frequently considered as Z-R relations (Michaelides et al., 2009). However, the parameterization attributes of the relation cannot be undermined.

In the present study, the characteristic of the vertical profiles of precipitable LWC over a period of 2 years using a vertically-pointing MRR are presented. Efforts were also focused on the analysis of statistics on the relationship between precipitable LWC, rain rates and radar reflectivity factor. The novelty of the present work is in the area of linking LWC and Z as against usual relation between Z and R.

2. Instrumentation and Theoretical Background

The instrument employed in this study is the vertically-pointing MRR installed at the department of Physics, Federal University of Technology, Akure (FUTA), a tropical station in the Southwestern part of Nigeria. The equipment is monitored by the Communication Research Group (CRG) of the department. MRR works by transmitting Frequency Modulated Continuous Wave (FM-CW) energy at 24.1 GHz frequency with a modulation of 0.5 - 15 MHz according to the height resolution specified (300 m - 10 m), that propagates through the atmosphere until some of the energy is reflected back by the hydrometeors. The power backscattered from each range sample volume is used to compute the power density spectra together with the first three spectral moments that correspond to the reflectivity Z (dBZ), Doppler velocity (ms^{-1}), and Doppler spectral width (ms^{-1}). The retrieval of range-resolved Doppler spectra follows the method described by Strauch (1976). The equipment is capable of measuring raindrop diameter between 0.16 to 4.8 mm with an accuracy of ±5% error limit. In order to give an account for the calibration, MRR uses the factory calibration and standard diameter categories supplied by the instrument manufacturer. Other details characteristics of the set-up is available in the work of Peter et al, (2002) and are not reiterated here. Table 1 presents the specification of the MRR.

The main measurement quantity of radar is the radar reflectivity factor Z, hereafter referred to as radar reflectivity. The Z of a meteorological target depends upon factors such as the number of hydrometeors per unit volume, the sizes of the hydrometeors, the physical state of the hydrometeors (ice or water), the shape or shapes of the individual elements of the group.

For water content particles that are small compared to the radar wavelength, the scattering is described by the Rayleigh approximation based on the equivalent spectral radar reflectivity factor Z_e (Strauch, 1976):

$$Z_e = \frac{\eta(f)df}{\frac{\pi_5}{\lambda^4}|K^2|}$$ (1)

Table 1. The specification of the MRR at the FUTA site.

Specification	MRR
Frequency	24.1 GHz
Power	50 mW
Height Resolution	160 m
Integration time	60 seconds
Height range	4800 m
Beam width	1 way, 3 dB

where $|K^2| \approx 0.92$, λ represents the wavelength, $\eta(f)$ is the spectral volume reflectivity as a function of frequency f. Within the Rayleigh approximation ($D << \lambda$) the integral, $Z_e = \int z_e \, df$ is identical with the usual radar reflectivity factor Z as (Peters et al., 2005):

$$Z = \int n(D) D^6 dD \qquad (2)$$

where $N(D) \, dD$ is the number of density of rain drops with equivalent diameter D in the interval dD. Equation (2) reveals that the variations of Z-R are strongly dependent on DSD variations (Kumur et al., 2011).

The drop size distribution $\eta(D)$ is calculated using the relation between volume reflectivity $n(D)$ and single particle scattering cross section $\sigma(D)$:

$$n(D) = \frac{\eta(D)}{\sigma(D)} \qquad (3)$$

$\sigma(D)$ is calculated by Mie-theory, and $\eta(D)$ is related to the measured spectral reflectivity $\eta(f)$ by (Peters et al., 2005):

$$n(D) = \eta(f) \frac{\partial f}{\partial v} \frac{\partial v}{\partial D} \qquad (4)$$

where $\partial f / \partial v$ is the Doppler relation, $\partial v / \partial D = -6.18 \exp(-0.6 \text{ mm}) (\rho_0/\rho)^{0.4}$ is an analytical fit to an empirical relation found by Gunn & Kinzer (1949), and $(\rho_0/\rho)^{0.4}$ describes the influence of air density on the fall velocity. The influence of vertical wind and turbulence was neglected here, which represents probably the most important source of error of this method (Joss & Dyer, 1972; Richter, 1994).

Radar reflectivity (assuming Rayleigh scattering), liquid-water content and rain rate were calculated with N the number of drops and D the drop diameter as follows.

To use radar as an indicator of LWC on the basis of $N(D)$, a relationship was obtained between LWC and radar reflectivity, Z. Mathematically, LWC and Z may be represented as:

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

where ρ_w is the density of water. LWC also follows the classic profile, in that it increases almost adiabatically from the base to the top of the cloud in relation in radar reflectivity. As per this paper profile is limited to the base of the cloud

since ice region is not considered for the precipitable LWC.

The actual relationship between LWC and Z based on the $N(D)$ of the Marshall-Palmer drop-size distribution gives (Green & Clark, 1972):

$$LWC = \frac{N_0 \pi \rho_w}{\left[720 \times 10^{18}\right]^{4/7}} Z^{4/7} \tag{6}$$

According to Green and Clark (1972), for $N_0 = 8 \times 10^6$ m^{-4}, and $\rho_w = 10^6$ gm^{-3}, (6) becomes:

$$LWC = 3.44 \times 10^{-3} \ Z^{0.571} \tag{7}$$

However, in our case, we intend to present results based on Z-LWC which is a reverse of (7) represented as:

$$Z = 3.44 \times 10^{-3} \ LWC^{1.75} \tag{8}$$

Hence, previous studies had deduced a general theoretical relationship between radar reflectivity and LWC as obtained from the cloud particle size distribution according to Atlas (1954) in the form of:

$$Z = a \cdot LWC^b \tag{9}$$

where a and b are coefficient may vary from one location to the next and from one season to the next. These coefficients will to some extent reflect the climatological characteristic of a particular location or season or more specifically the type of rainfall for which they are derived from.

The rain rate, R which is a measure of the intensity of rainfall is obtained by calculating the amount of rain that would fall in a given location over a given interval of time if the rainfall intensity were constant over that time period. The rate is typically expressed in terms of length (depth) per unit time, for example, millimeters per hour, or inches per hour (AMS, 2007). The rain rate for each one minute $N(D)$ sample was computed using the relation:

$$R = 6\pi \times 10^{-4} \times \int_0^\infty N(D) D^3 V(D) dD \tag{10}$$

where R is the rain rate (mmhr^{-1}), D is the rain drop diameter (mm), $V(D)$ is the terminal velocity of the drop in (m/s).

3. Dataset

The dataset used in this study was collected during a period 2-year (between January 2011 and December 2012) data collection from a vertically-looking MRR. The data of liquid water content at different height with 30 range gates of resolution of 160 meters, up to the few of meters height of 4800 meters is measured with an accuracy of ±5% error limit. The equipment sampled at every 10 seconds and integrated over one-minute. This is achieve among other factors to reduce errors associated with mixing samples representing distinct precipitation processes. Attenuation corrections were applied to the MRR based on the path-integrated attenuation (PIA) according to Peters et al. (2010). However this correction is only applied to PIA ≤ 10 dB, and for this reason uncorrected data

were not employed in the rain water analyses. Moreover, updrafts and downdrafts can cause significant variations in the raindrop size distribution estimates, which are directly reflected in the reflectivity retrieved by the MRR (Peters et al., 2005). Hence, the presence of deep convection can cause erroneous liquid water content in MRR measurements; therefore, such data were not considered in this study. Other details characteristics of the set-up is available in the work of Peter et al. (2002) and are not reiterated here

In processing the data, some of the data have been discarded if the vertical profile of liquid water content is found to be discontinuous at same height as a precautionary measure. Most of the data were sampled in stratiform clouds, associated with frontal systems. These were identified by choosing a sensitivity threshold of 0.005 gm^{-3} for the LWC while disregarding when $LWC < 0.005$ gm^{-3} which is regarded as clear air (Korolev et al., 2007). In addition, the negative values of the LWC that are often caused by contamination due to echoes from non-hydrometeors, such as insects, near the cloud base which have similar reflectivity's to those of liquid water clouds were also filtered off (Clothiaux et al., 2001). We have also applied a minimum rain rate threshold of 0.2 mm h^{-1} to remove accumulated samples prone to large sampling errors.

For the estimation of the Z-LWC, the resulting relationship may be sensitive to both the input data as well as the method used in the calculation (Hagen & Yuter, 2003). Based on the quadratic relation in (8), the linear relation is simplifying as:

$$\log_{10}(Z) = \log_{10}(3.44 \times 10^{-3}) + (1.75) \log_{10}(LWC) \qquad (11)$$

4. Results and Discussion

The monthly mean LWC over the years 2011 and 2012 and the mean average are shown in Figure 1. The profile shows a seasonal variation in the monthly mean result, as higher values are obtained at the rainy season months and lower values in the dry months which are one of the features of tropical climate. Year 2012 recorded higher value of LWC of about 1.15 gm^{-3} in the month of July as against 0.82 gm^{-3} observed in the month of June for the year 2011. However, regardless of the year, the dry months continue to experience minimum values of LWC.

### 4.1. Diurnal Variation of LWC Profile

Theoretically, LWC increases with altitude a unique function of height above the base of the cloud. However, in a relatively thin cloud (thickness of the cloud less than 500 m), LWC is expected to change linearly with altitude because of the entrainment of drier air, mixing, precipitation fallout and radiative heating/cooling. Figures 2(a)-(c) present the vertical profile of LWC for some typical days during the end of the dry season months-8th March, 2011, beginning of the dry season months-7th November, 2011 and the peak of the rainy season months-5th September, 2011 in the year 2011 respectively. Nearly all the results show that LWC attains peak values at the height of about 4160 m which coincides with the
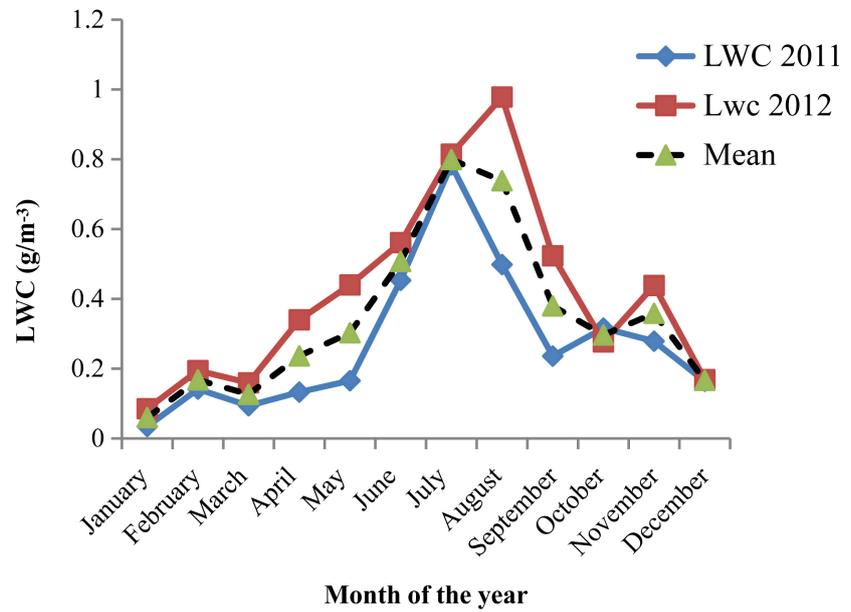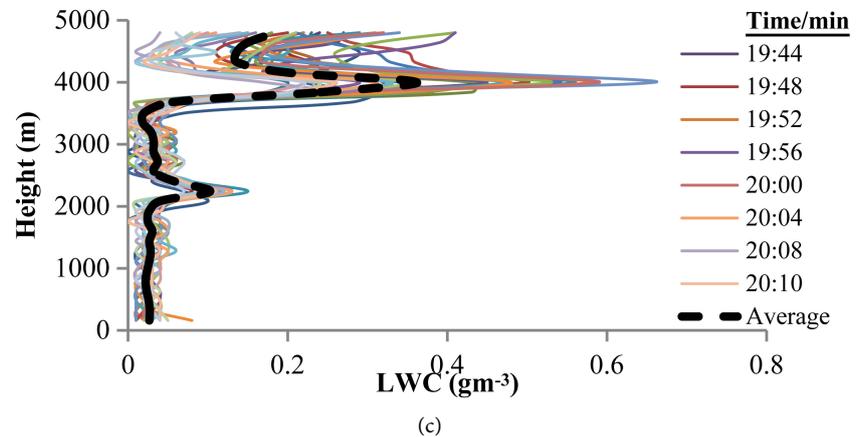
Figure 1. Variation of monthly Mean *LWC* for 2011 and 2012 with mean of the years of study.

(a)

(b)

(c)
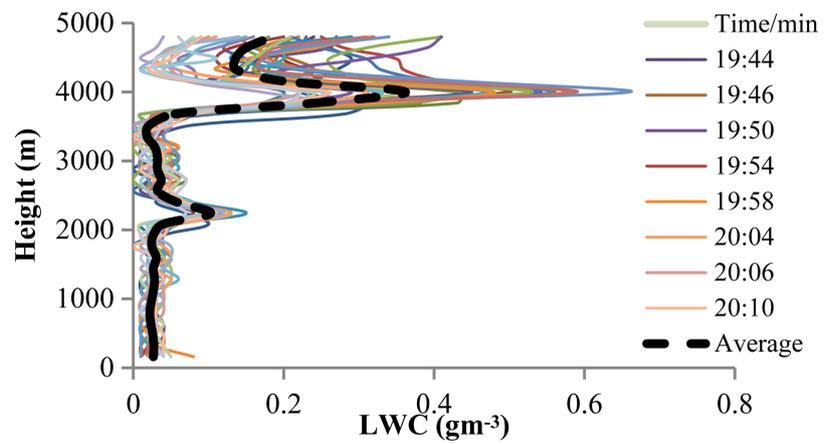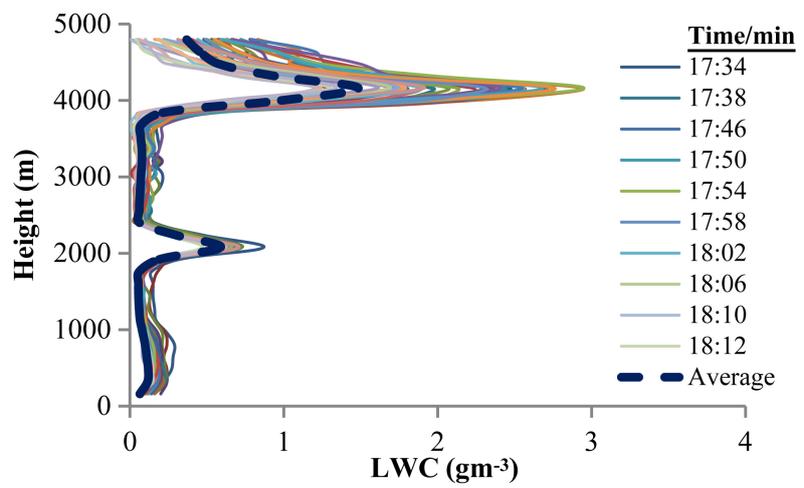
Figure 2. Vertical profile of *LWC* for some typical days during (a) a month in dry season months-8th March, 2011, and (b) beginning of the dry season months-7th November, 2011 and (c) the peak of the rainy months-5th September, 2011.

freezing height level (rain height ~4250 m based on ITU rain height relation) for the study location as a result of the enhancement due to high reflectivity from melting ice at this height (Ojo et al., 2014). The result indicates the likelihood relationships between the melting layer height and the *LWC*. This is obvious since only the liquid fractions of condensed water in mixed-phase clouds could be detected by the MRR. **Figure 3(a)** & **Figure 3(b)** also present the vertical profile of *LWC* for some selected days for the year 2012. The results presented in the plots follow the same trend, except for January where *LWC* attains peak values at the height of about 4450 m.

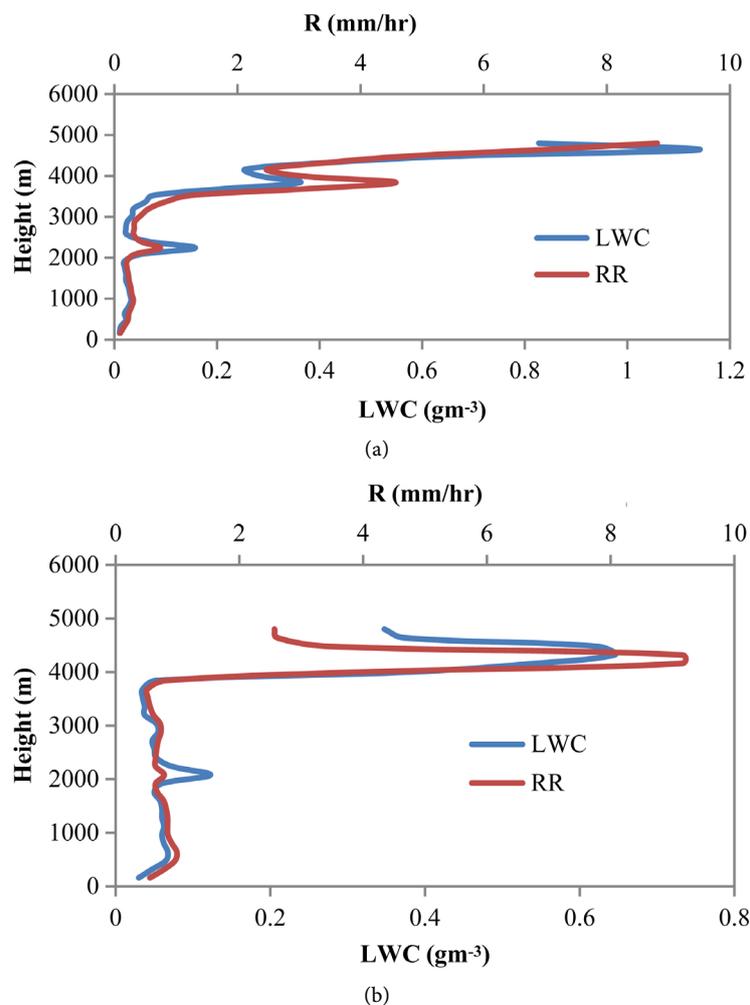## 4.2. Monthly Variation of the Vertical Profile of *LWC*

Figure 4(a) and **Figure 4(b)** present the variations in the amount of daily rain rates with *LWC* for the month of March, 2011 and the month of September, 2011 respectively. As usual the two months were selected based on the dry and rainy season respectively. Results from the vertical profiles show that rain rate increases with the amount of cloud *LWC* to a peak around 4160 m. This may be related to decreased air density with altitude adiabatic cooling, which occur with water vapor precipitating out of the air parcels, the precipitation rate for a given drop size distribution increase with altitude. The likelihood of the relationship between the rain rates, *LWC* and melting layer height could also be noticed. This is in agreement with the earlier observation in the previous section. It has also been reported by Paul & Paul (1985) that the selected months are predominated by stratiform cloud hence the presence of stratiform rain. Similar results are presented in **Figure 5(a)** & **Figure 5(b)** for the selected months in the year 2012.

4.3. Distributions of Mean Values of *LWC*

Figure 6(a) and **Figure 6(b)** show the frequency distribution of the mean observed *LWC* for both precipitating and non-cloud over the site for the years 2011 and 2012 respectively. It could be seen that the high value of *LWC* (0.13 - 0.45)
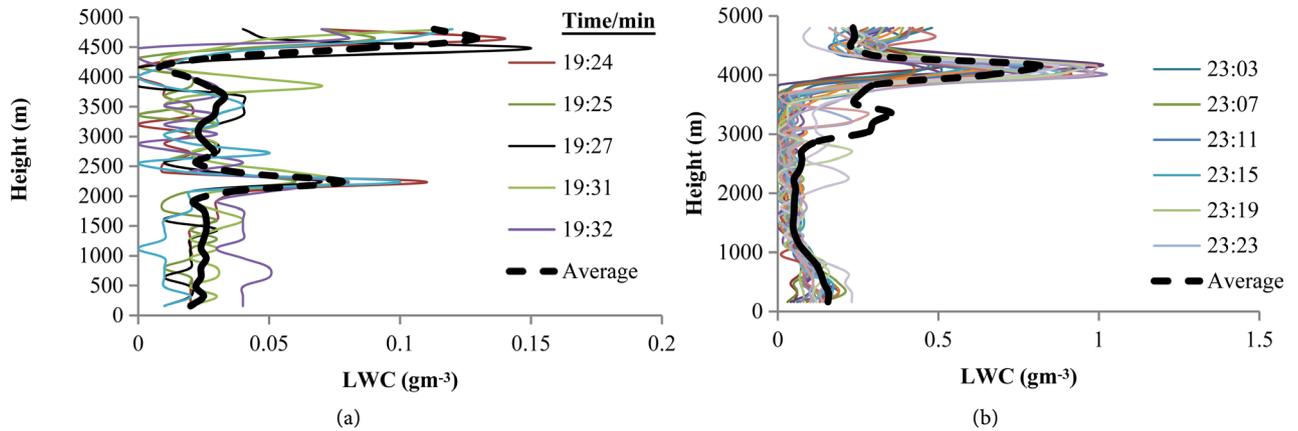
Figure 3. Vertical profile of *LWC* for some typical days during (a) a month in dry season months-5th January, 2012, and (b) the peak of the rainy months-12th October, 2012.
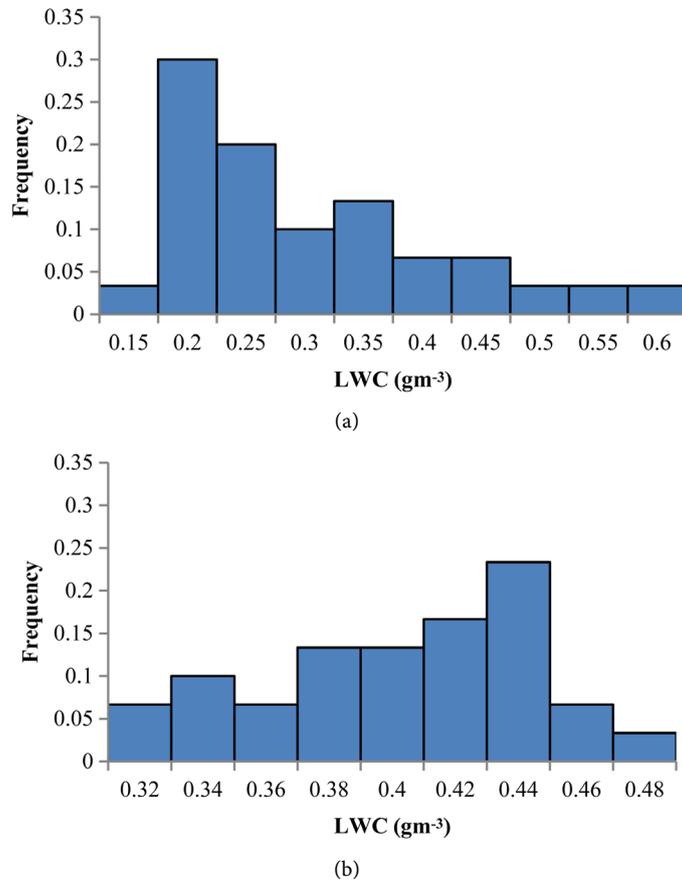

Figure 4. Variation of vertical profile of *LWC* and Rainfall Rate (R) for (a) the month of March, 2011 and (b) September, 2011.

dominates in the year with 78% in the distribution. In **Figure 6(a)** for example, the maximum distribution of the *LWC* is about 0.3 gm^{-3}. Also the overall mean
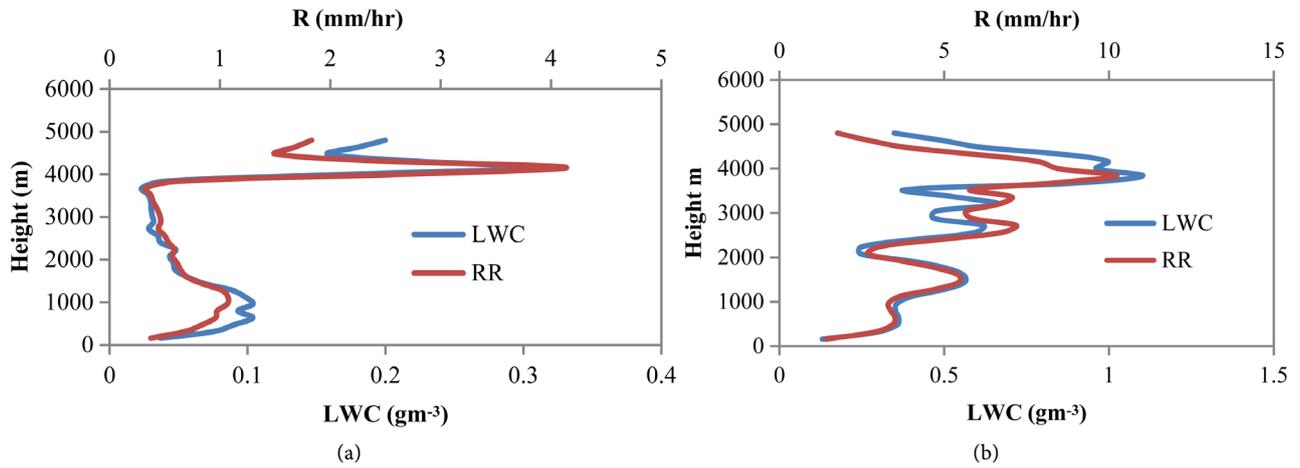
**Figure 5.** Vertical profile of LWC and rainfall rate (R) for the month of February, 2012 and (b) October, 2012.

Figure 6. Frequency distributions of LWC mean values for the year (a) 2011 and (b) 2012.

average of LWC observed was 0.3 gm^{-3} while the mean and median were 0.27 gm^{-3} and 0.38 gm^{-3}. Similar results were also presented for the months in the year 2012 as shown in **Figure 6(b)**. Generally, year 2012 reveals fairness in distribution percentage of LWC mean values than in 2011, though higher value of LWC was obtained in 2011.
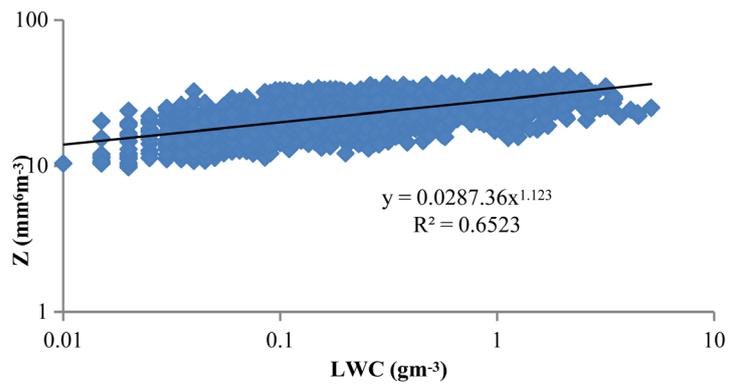
4.4. *Z-LWC* Relation

Since one of the objectives of this paper is to deduce the relationship between the radar reflectivity Z and LWC at various heights for the period under consideration based on ground based Radar. **Figures 7(a)-(c)** and **Figures 8(a)-(c)** present the relation at some selected heights of 160, 4160 and 4800 m respectively for the years 2011 and 2012 individually. Heights 160, 4160 and 4800 m were selected to represent the lower height of the radar, the height at which the melting layer was detected and the upper height of the radar respectively. While the summary of the yearly correlation is also presented in **Figure 9**.

(a)

(b)

(c)
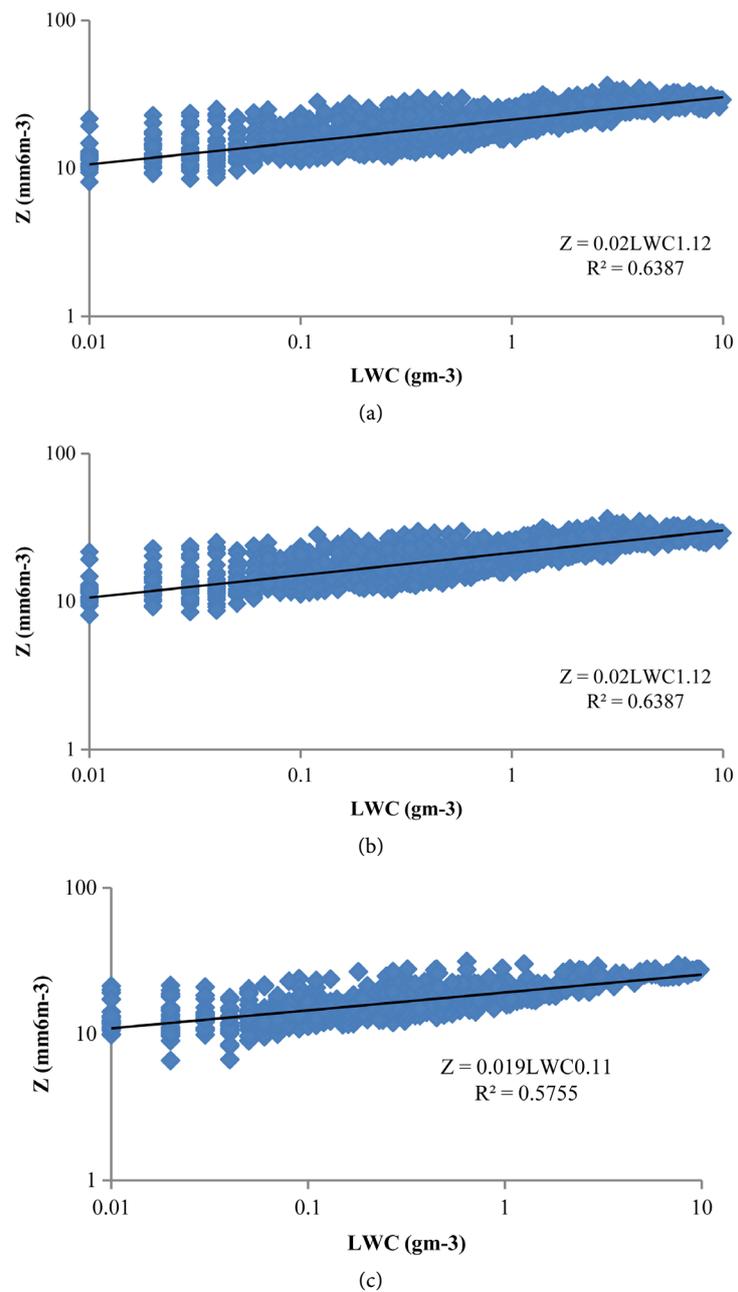
Figure 7. *Z-LWC* relation at heights (a) 160 m, (b) 4160 m and (c) 4800 m for the year 2011.

(a)

(b)

(c)
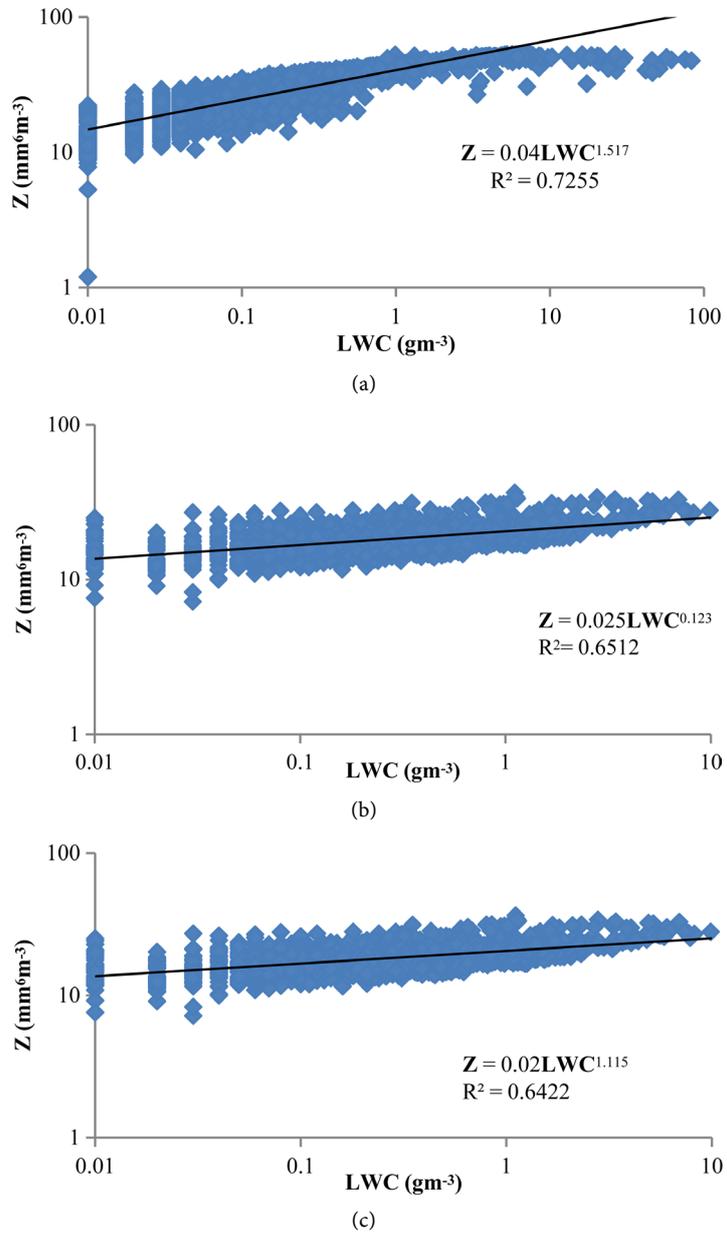
Figure 8. *Z-LWC* relation at heights (a) 160 m, (b) 4160 m and (c) 4800 m for the year 2012.

Figure 9. *Z-LWC* relation at all the heights for the 2 years of study.

Table 2. Comparison of Z-LWC relations at some locations.

Source	Location	Z-LWC Relation
Atlas (1954)	Massachusetts, USA	$Z = 0.048 LWC^{2.0}$
Sauvegeot and Omar (1987)	Pyrenees, France	$Z = 0.03 LWC^{1.31}$
Fox and Illingworth (1997)	The North Atlantic	$Z = 0.012 LWC^{1.16}$
Present Study		
2011	Akure, Nigeria	$Z = 0.024 LWC^{1.19}$
2012	Akure, Nigeria	$Z = 0.035 LWC^{1.35}$
Combined 2-years of study		$Z = 0.041 LWC^{1.64}$

The results show that irrespective of the selected heights and the year, there exist a strong correlation between Z and LWC, since R^2 is greater than 0.5. Although, empirical relations between Z and LWC do not appear frequently in literature, despite their utility for comparison with aircraft in situ data and numerical model output and their relative simplicity compared to a Z-R relation (Hagen & Yuter, 2003). Results in **Table 2** are presented to show the comparison between Z-LWC relations obtained from the present study with those obtained by Atlas (1954), Sauvegeot & Omar (1987) and Fox & Illingworth (1997). The most striking results from the table is the diversity of the Z-LWC coefficients fitted over this single dataset. For example, in the Z-LWC relations, the pre-factors takes values in the range 0.024 up to 0.035 for year 2011 and 2012 respectively, while the exponents are in the range of 1.19 up to 1.35. In addition, the parameters a and b derived from the relation based on the power law are also in agreement with those obtained from literature as presented in **Table 2**.

5. Conclusion

Analysis of the vertical profile of precipitable LWC over a period of 2-year in a tropical location have been presented. The results show strong seasonal variation of cloud LWC, which is one of the features of tropical climate. Further results show a general trend in the vertical profile of LWC for most of the days and months considered with maximum peak at around 4160 m followed by a decline at the cloud top. The LWC was also varied linearly with rain rate at all the months. A strong correlation was also observed between rain rates and LWC. The peaks of R show that LWC concentration is at the same height with rain height. In the frequency distribution of LWC, the vast majority of the LWC profiles has low LWC less than 1 gm^{-3} while the maximum observed LWC for period of study was about 3.18 gm^{-3}. The analysis of Z and LWC also shows a strong correlation to some certain extent as the percentage of correlation is more than 70%; hence the use of radar in retrieving LWC from radar reflectivity is reliable. Overall results will serve as good tools for system engineers to assess the level of absorption, reflection and attenuation of electromagnetic signals as a result of precipitable LWC along the transmitting paths in the region. The novelty of the present work is in the area of linking LWC and Z as against usual relation between Z and R.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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