Estimation of Rainfall Intensity From First Observation Weather Radar Reflectivity Data Over Upper Blue Nile Basin, Ethiopia

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ABSTRACT Weather radar has been to measure reflectivity power from precipitation. It is suitable to cover large area. Bahir Dar weather radar is installed at Washera in the north west of Ethiopia for the first time. Ground-based weather radar precipitation observation is helpful to estimate the reflectivity (Z) and rain rate (R) relations. In Ethiopia, a large study has been conducted on precipitation using rain gauge network data. Gauge precipitation data are not available at a required temporal and spatial distribution over Upper Blue Nile Basin (UBNB), Ethiopia because of insufficient network and density of rain gauges. Most importantly, we do not know the amount of rainfall on the Lake Tana body in Bahir Dar city. Accurate and precise measurements of rainfall from weather radar are essential to supplement the limited characterization of spatial and temporal gauge measurements. But in the case of UBNB, Ethiopia none reported using radar data because of non availability of radar instrument before in 2016. Therefore, for the first time we attempted the estimation of precipitation from weather radar reflectivity data by developing Z-R relation empirical model. For developing Z-R relation model, hourly and daily reflectivity and rain rate data obtained from Bahir Dar weather radar and Bahir Dar gauge station. From our observation the value of the parameters 'a' and 'b' are found to be 50 and 1.02 respectively. The range of R from empirical Z-R relation is varied from 5.4 to 23.5 mm. Similarly, from the gauge direct observation varied from 4.2 to 22.6 mm. The error deviation of R between the gauge observation and the Z-R relation model are varied from -12.9% to 12.5%. In general, to estimate rainfall data from weather radar reflectivity is quite useful to supplement the irregular and sparse distributions of gauge station in developing countries, such as UBNB, Ethiopia. Hence, the outcomes from this study will be considered for future configuration and calibration of the radar system in Ethiopia.

KEYWORDS: Weather radar; Rain rate; Reflectivity; Rain type; Bahir Dar

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TRANSACTIONS ON SCIENCE AND TECHNOLOGY

INTRODUCTION

Rainfall is the main driven force in hydrology and meteorology which studies the movement of water on the Earth's surface and the atmosphere. A high accuracy rainfall rate (R) measurement is considerable interest for meteorologists, hydrologists, policy makers and researchers to take a better decision. Rain Gauges are reliable instruments for point surface rainfall measurement, but the spatial representativity is limited (Chilson, 2008). Thus, there have been considerable interests in utilizing remote measurement such as weather radar and satellites. Since, it provides spatially and temporally continuous measurements (Dhiram & Wang, 2016). The estimation of R at the ground can be derived from radar reflectivity (Z) measurements. For many years of practice they have attempted to find a useful relation between Z and R (Alfieri *et al.*, 2010). In order to use weather radar data at the ground surface Z should be converted to R by Marshall & Palmer (1948) formula ($Z = aR^b$), where 'a' and 'b' are empirical constants which can be used to estimate the rainfall amount (Marshall & Palmer, 1948). Hence, an algorithm should be developed and calibrated against the rain gauge networks. After improving Z-R relation mathematical model, we can use R as ground-based scanning precipitation in short-term weather and flood forecasting (Ulbrich & Atlas, 2007).

BACKGROUND THEORY

Hydrologists and meteorologists from different parts of the countries are interested to determine 'a' and 'b' parameters from Z-R relation empirical model. For example Nzeukou *et al.* (2002) uses a disdrometer technique to measure number of drops $N(D)$ for convective rain type which found to be $Z=31R^{1.9}$ over Brazil. In Guyana using S-band Doppler weather radar Dhiram & Wang (2016) calculated $Z=250R^{1.2}$ for Guyana region. In the case of Netherlands, using the classical exponential raindrop size distribution the Z-R relation has been proposed $Z=238R^{1.50}$ (Uijlenhoet, 2001). In Libya utilizing C-band weather radar observations and its correlate studies with gauge data and regression methods obtained $Z = 116\ R^{1.87}$ (Kamil & Medhat, 2009) and with Italy Z-R relation is derived using adaptive calibration method (Andrea, 2015). Coming to Ethiopian context, in recent past a large studies have been conducted on precipitation using rain gauge network data, but none reported using radar data because of non availability of radar instrument before in 2016. One of the disadvantages of rain gauge data are not found with a required temporal and spatial distribution and it cannot identified precipitation types over UBNB; moreover, accurate estimation of rainfall on the Lake Tana is very difficult (Onyutha, 2015; Abera *et al.*, 2016). Most importantly, we do not know the amount of rainfall on the Lake body. We are estimated from inland rain gauge data. To resolve this challenge, very recently in the year of 2016, the C-band weather radar is installed at the Washera (the north west of, Ethiopia) located 100 km from Bahir Dar city. So, for the first time an attempt has been made the estimation of precipitation from weather radar reflectivity data by developing Z-R relationship empirical model. We also estimated the spatial and temporal distribution of R and Z by determining precipitation types around Lake Tana at Bahir Dar region.

SYSTEM DESCRIPTION OF ETHIOPIAN WEATHER RADAR

The first weather radar is installed in Ethiopia at Washera in the north west of Ethiopia around Bahir Dar city in 2016. Bahir Dar, Ethiopia weather radar has its own specifications, such as pulls repetition frequency (PRF), scanning rate, antenna width, average power and polarization describes in Table 1.

Table 1. Bahir Dar Weather Radar Specifications

Parameters	Values
Band	C
Transmitter	Magnetron
Frequency	5.5-5.7 GHz
Peak power	250 kW
Average power	300 W
PRF	600 Hz
Antenna diameter	4.5 meter
Gain	45 dB
Polarization	Dual (vertical and horizontal)
Maximum scan rate	40 deg/second

This weather radar is operating with a Constant Altitude Plain Position Indicator (CAPPI) scanning technique in a 250 km radius. Weather radar couldn`t measure rainfall directly but it measures reflected power signals. It has magnetron transmitters which emitted radio electromagnetic radiation with a component of electric and magnetic fields. After strikes the target it reflected back to the weather radar receiver. Its receiver converted these electric and magnetic field components into the voltage. The amplitude of the voltage gives the strengths of Z. Reflectivity is a power it does not useful for meteorologists and hydrologists. Therefore we must be converted Z to R using Z-R relation model.

STUDY AREA DESCRIPTION, DATA AND METHODS

The procedure for evaluating radar-based rainfall fields requires (1) to obtain Z field from the radar and (2) to relate Z in to R which obtained from Bahir Dar gauge station.

Description of the study area

Upper Blue Nile basin (UBNB), Ethiopia is located between 7⁰40` to 12⁰5` N and from 34⁰25` to 39⁰49` E with a drainage area of about 176, 000 km². Lake Tana and Abby River basin are the main water bodies in UBNB region (Abera *et al.*, 2016). Bahir Dar city is located within UBNB, Ethiopia and it is the water tower of Lake Tana and Abby River basin. The spatial variation of rainfall over this region is very dynamical because of the interaction between locale moistures from the Lake and Abby River with the global moistures on the variable topography area. That is the reason to install weather radar on UBNB to extract accurate rainfall data.

Data sources

Hourly and daily Z data is obtained from Bahir Dar weather radar using CAPPI products. CAPPI product scans the area at constant altitude with the radius of 250km. We selected CACPPI product from the other products such as Plane Position Indicator (PPI), Max product, top product and Rain Height Indicator (RHI) products because, it gives Z, height and storm velocity data information. It gives also a clear image/very good data quality relative to other products. Hourly and daily R data is obtained from Bahir Dar Meteorology Agency (Bahir Dar gauge station).

Mathematical methods

In this study we are applied Rayleigh scattering to collect Z data from the radar. Because 'a' and 'b' parameters depend on rain drop size distribution which stated in Equation (1).

$$Z = \int_0^\infty D_0^6 N_0(D_0) dD_0 \tag{1}$$

where Z is reflectivity factor in mm⁶/m³, D_o is raindrop diameter in mm at sub cloud level, N_o is number of drops per cubic meter at sub cloud level (Vignal & Krajewski, 2001; Ulbrich & Atlas, 2008). At some cloud level the size of rain drops are not the same, some of them greater than the wavelength of the signal and the remaining less than the wave length of the signal. Hence, it is difficult to determine 'a' and 'b' parameters. However, higher droplets are unstable which breaks up to small and uniform stable droplets that falling from some cloud level to the ground (Torres *et al.*, 2004). Rayleigh scattering is responsible the size of rain droplets less than the wave length of the signal. So, we collect hourly and daily based distributions by applying Rayleigh scattering to evaluate 'a' and 'b' parameters. As mentioned earlier, radar does not directly measures rainfall but it measures reflected echo powers. Therefore, Z can be converted into R using Equation (2).

$$Z = aR^b \Rightarrow R = \left(\frac{Z}{a}\right)^{1/b} \tag{2}$$

where, 'a' and 'b' are parameters depended on drop size distribution which provided in equation (1). Equation (2) clearly shows the Z-R relation mathematical equation. But our ultimate goal is determined 'a' and 'b' parameters by using Ethiopian weather radar Z data and Bahir Dar gauge station R data. The mathematical formulation clearly observed in equation (2)-(8). Applying natural logarithms on both sides of equation (2) is obtained equation (3).

$$\ln Z = \ln a + \ln b \tag{3}$$

Let y=lnZ, m=lna, n=b and x=lnR; then

$$y = m + nx \tag{4}$$

Equation (4) makes a linear function, m and n are the intercept and the slope of a function, respectively.

$$Z=[z_1 \ z_2 \ z_3 \ldots z_n] \text{ and}$$
$$R=[r_1 \ r_2 \ r_3 \ldots r_n]$$

where $z_1, z_2, z_3 \ldots z_n$ and $r_1, r_2, r_3 \ldots r_n$ are number of Z from weather radar and R data from the gauge respectively.

$$b_n = \frac{\ln(Z_{n+1}/Z_n)}{\ln(r_{n+1}/r_n)} \tag{5}$$

$$b = \frac{\sum_1^N b_n}{N} \tag{6}$$

where b_n is logarithmic ratio of Z and R, b is the average value of b_n which is the slop of the function we can see from equation (4).

$$a_n = \frac{Z_n}{r^{b_n}} \tag{7}$$

$$a = \frac{\sum_1^N a_n}{N} \tag{8}$$

where a_n is the ratio of n number of Z and R with respect to b, a is the average value of a_n . The coefficients 'a' and 'b' of equation (2) are estimated by simultaneous equation using *Z* and *R* data. The data is analyzed by the above equation with the help of MATLAB and IRIS programs.

RESULT AND DISCUSSION

In this section we were analysis the temporal and spatial variability of rainfall after determined the Z-R relation empirical model parameter values. We are estimated the frizzing point of rainfall over the study area. A gauge measurement is not giving precipitation types. Developing Z-R relation model weather radar Z data from liquid rain is essential to reduced uncertainty. Because, the Z strength is different among drizzle, liquid rain, sleet, snow, graupel and hail. After determining the observation types Z converted to R for meteorological and hydrological purpose.

Reflectivity profile for different altitude

CAPPI product is a horizontal cut through the atmosphere; it scans the target from the ground to some height (0 to 9 km). In this product hydro-class data can be inferred from Z (dBZ) profile directly from the radar that shows the classification of drizzle, liquid rain, sleet, snow, graupel and hail observations. A precipitation type is clearly observed in Figure 1.

The constant line that spans from 0 to 2 km shows the liquid rain. The increasing trend of the altitudes as shows from 2 to 3 km in Figure 1 is the melting ice (droplets at outer surface are liquid water but at the center is snow). The height at 3 km illustrates the freezing level. The descending pattern, which spans from the height 3 to 4 km, demonstrates the sleet whereas from 4 to 5 km we can observe snow. Similarly, 5 to 7 km informs us the rainfall may obtain from graupel and above 7 km it is possibly from the hail. The increasing order of rain type density is hail<graupel<drizzle/snow<liquid rain<melting ice. Reflectivity directly related to the density of the target. Not all echoes on weather radar are due to rain or snow. Non-meteorological returns may be caused by; the Earth's surface and stationary objects on it, transient objects (ships, aircraft, birds,

insects), interference from other sources, such as nearby radars (Bech *et al.*, 2007). The most common non-meteorological echoes are ground echoes. This occurs when a radar beam intersects any surface feature, such as high ground, buildings and trees. But we can identify meteorological and non meteorological targets because the radar is dual polarization which shows the shape of the targets.

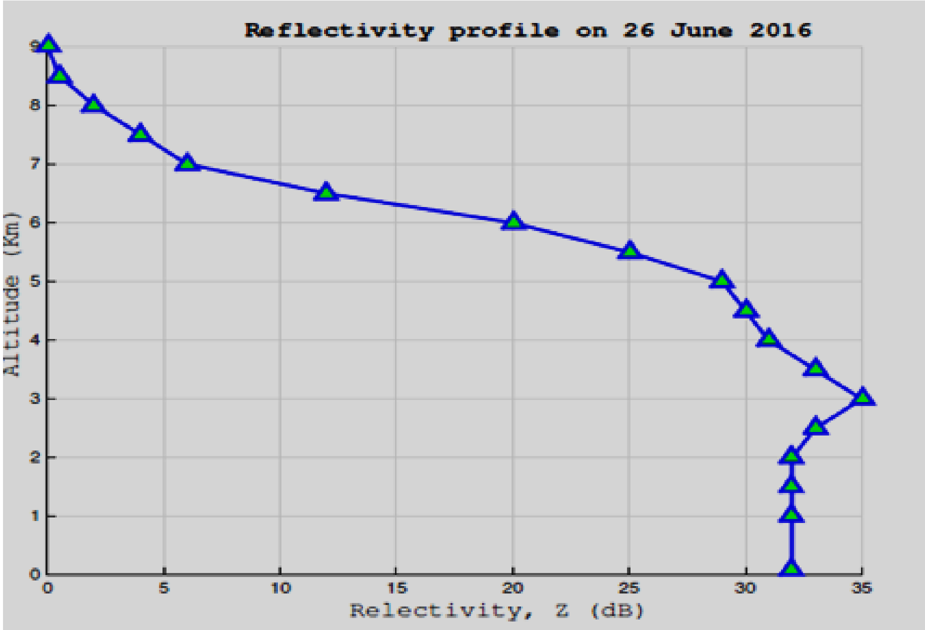

Figure 1. Reflectivity profile on 26 June 2016 for different altitude.

Z-R relation empirical model

Preliminary data has been collected from Bahir Dar radar in 2016. For this finding, the Z-R relation mathematical model parameter values of 'a' and 'b' are found to be 50 and 1.02 respectively. The estimated parameter values were nearly similar to the coefficients 'a' with previous reports of Brazil and the exponents 'b' with Guyana literature as reported by the pervious researchers (Nzeukou *et al.*, 2002; Dhiram & Wang, 2016). After determining 'a' and 'b' parameters we observed the hourly and daily distribution of rainfall rate over UBNB around Bahir Dar. In this paper the daily variation of R from empirical Z-R relation model is varied from 5.4 to 23.5 mm and the range of R from the gauge direct observation is varied from 4.2 to 22.6 mm at Bahir Dar gauge station on June 22-28, 2016. It reveals that the estimated value is greater than direct observation, because R observed from rain gauges are suffered from some limitations such as, errors attributed due to airflow (wind direction and speed), unrepresentative orientation and exposure of the gauge, protection problem and Evaporation from within the cylinder and overflow (Dhiram & Wang, 2016). Even though weather radar has limited applications for the usual longer term weather forecasts, it is extremely useful to issue warnings when severe weather develops rapidly in around radar location. A significant problem is that the Z-R relationship values vary as a function of precipitation types because of the differences in raindrop size distributions. Therefore, the Z-R relationship is suitable for the study area climate is:

$$Z = 50\, R^{1.02}$$

Based on the threshold value, Z can be classified as straitform rain type Z less than 38 dBZ) and the convective rain type Z is greater than 38 dBZ (Wilson & Tan, 2001; Kumar, 2011). Our analysis of daily weather radar data 65% of Z is greater than 38 dBZ. Hence, we conclude that Ethiopia has 65% of convective rain type due to the convective scheme of the moisture from Lake Tana and 35% of straitform rain type from the global dynamics. The diameter of rain drop size straitform rain type greater than convective rain type (Kumar *et al.*, 2011). R from empirical Z-R relation and the gauge direct observation are well observed as we can see in Figure 2.

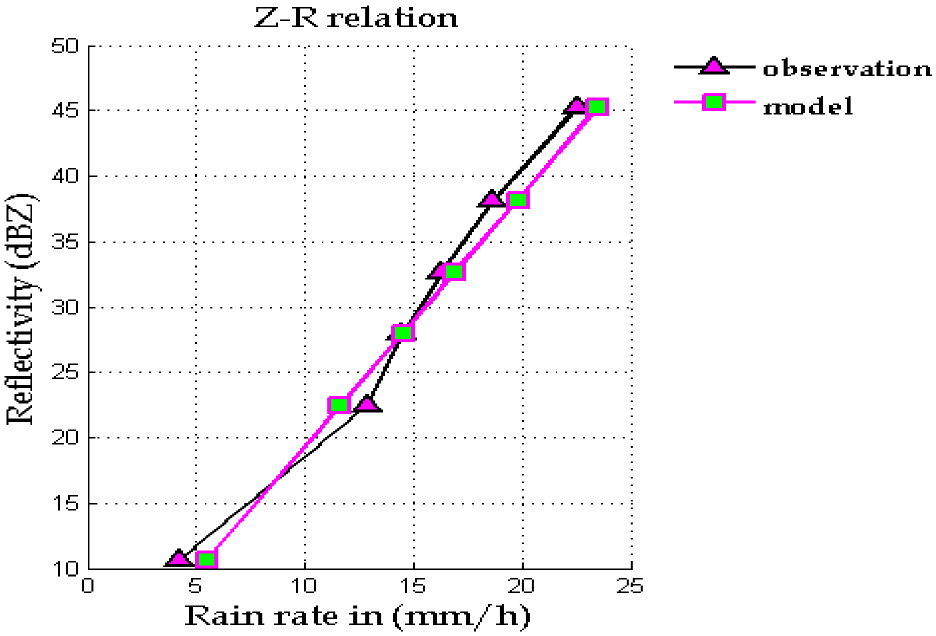

Figure 2. Rain rate verses reflectivity between the observation and empirical model over UBNB.

The deviations of the output compares Z-R relation empirical model from the radar and gauge direct observation are illustrated by the error bar given by Figure 3.

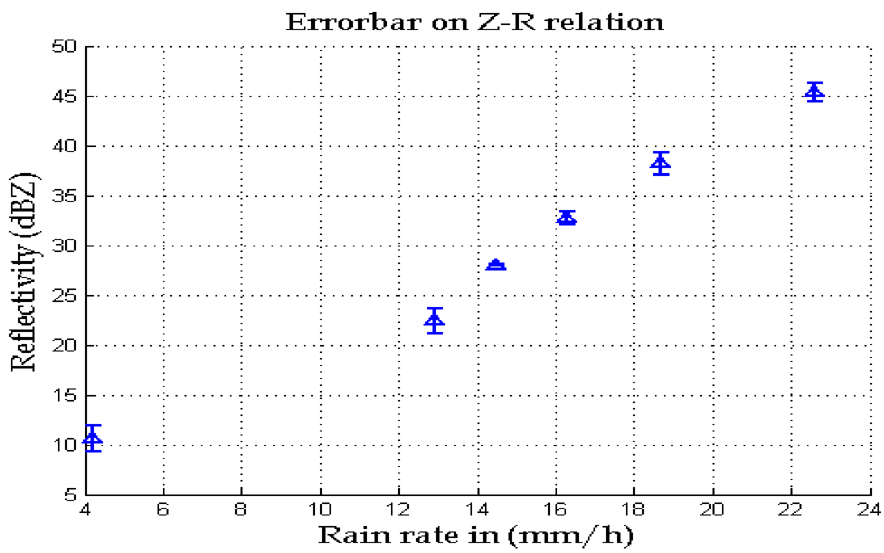

Figure 3. Error bar from rain rate verses reflectivity between the observation and empirical model.

It is clearly shows that there was a less variation on the deviations between the radar empirical Z-R relation model and the gauge direct observation which values is varied from -12.9% to 12.5%.

Hourly temporal variations of R and Z

R and Z are displayed by the top and the bottom panels of Figure 4 respectively. The two figures R and Z extracted from similar time stapes. R extracted from weather radar Z-R relation model but Z extracted directly from the weather radar simulation model as suggested by Wilson & Brandes (1979).

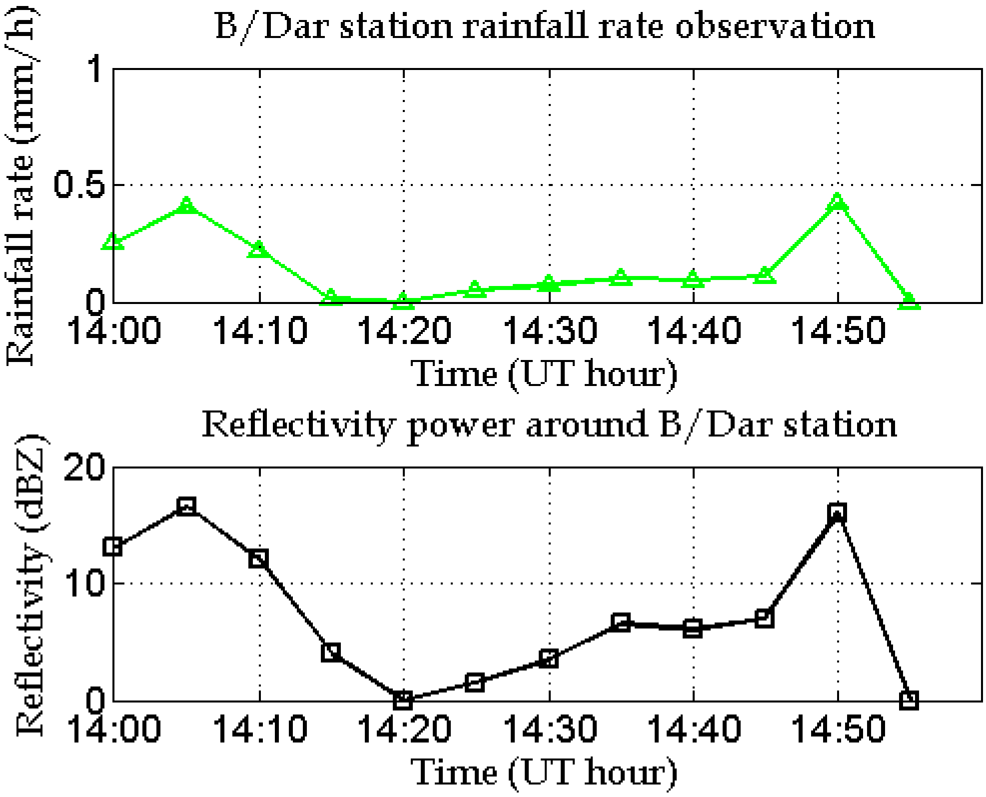

Figure 4. Hourly variations of R and Z profile at Bahir Dar gauge station on 13 July 2016.

At the start time of 14:00 UT hour, R from weather radar Z-R relation model found to be 0.25 mm/h but started from 14:05 to 14:15 UT hour it was extremely decrease. From 14:15 to 14:45 UT hour slightly increases. At 14:50 UT hour the most maximum intensity is observed. At 14:55 UT hour zero observation is recorded. Rainfall is showed as very dynamical temporally variable in the atmosphere as we can see from Figure 4. The same is true Z is varied with time due to strengthen of storms. At the start time of 14:00 UT hour, the weather radar Z power is found 12 dBZ. But started from 14:05 to 14:15 UT hour, it was extremely decreased with the proportional of R but in different magnitude. From 14:15 to 14:45 UT hour slightly increases; at 14:50 UT hour the most maximum Z is observed with value is found to be 18 dBZ. At 14:55 UT hour zero Z observation is recorded refer the bottom pane of Figure 4. The highest the storm reflected much power to the radar receiver and lowest storm reflects less power to the radar receiver, because transmitted input signal is passed through the atmosphere in less density storms.

Daily spatial variations of rainfall

The daily spatial distribution of rainfall during the period of 22-28 June, 2016 over UBNB is demonstrated in Figure 5. The first figure corresponds to June 22 reveals in the northern part of the radar the heaviest rainfall is observed. But next day on June 23, the middle and northwest of the radar didn't have rainfall observation except southern parts. On June 24 western and eastern parts have not get sufficient rainfall. On June 25 and 27all parts of UBNB has got optimum rainfall except western part of the radar. Finally from Figure 5 concluded that rainfall shows very dynamical spatial variability in the atmosphere. Conversely in all days rainfall isn`t recorded for western part of the radar. It didn't mean there is no rain, we assume that there might be rain, but due to ground clutters the radar couldn't observe the rainfall, since transmitted signals reflected back near to the radar before to reach the further rainfall targets.

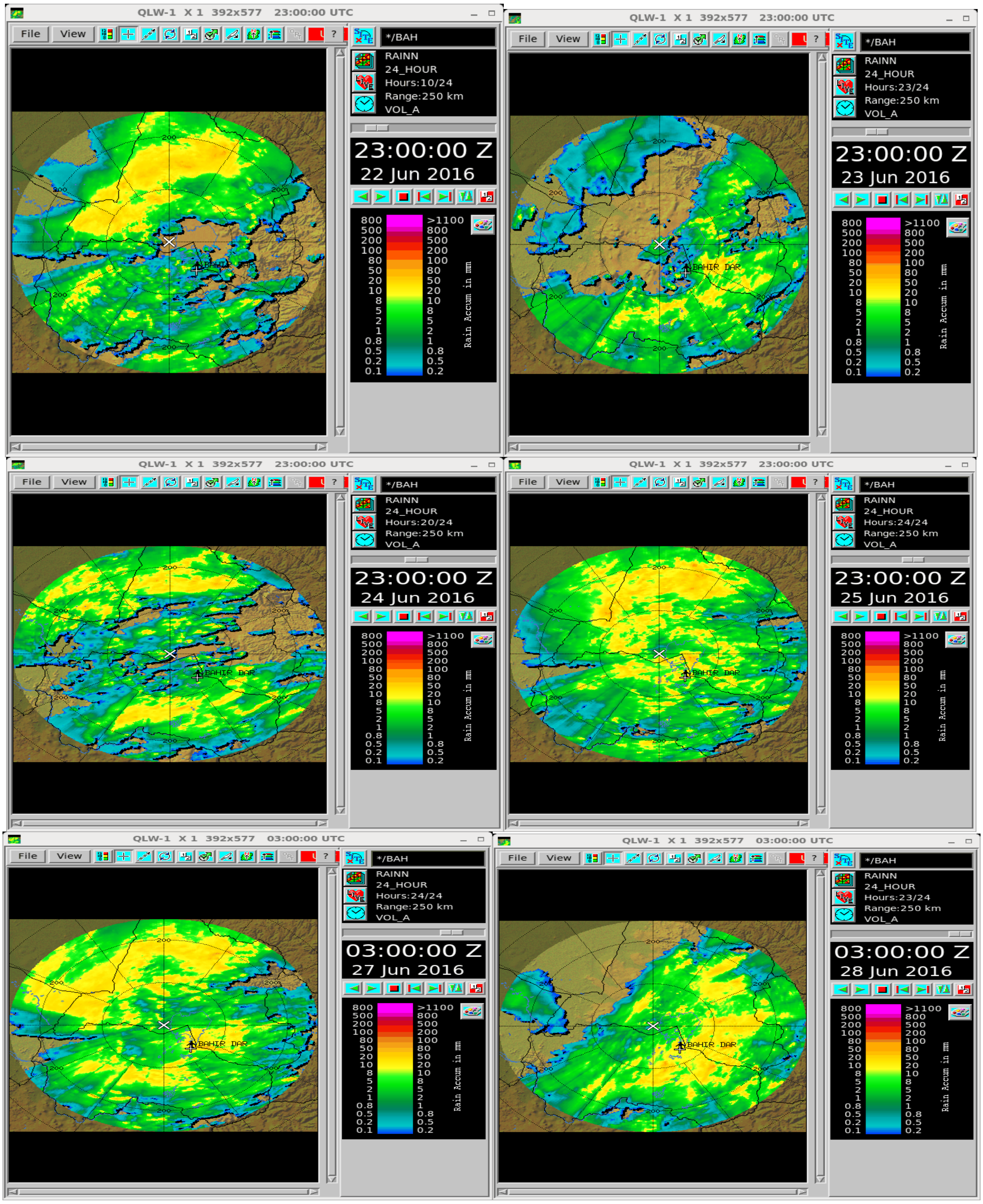

Figure 5. Daily spatial distribution of rainfall over the study area on 22-28, June, 2016.

When severe weather occurs or warning is issued by the National Weather Service, radar images is provided that the areas surrounded by yellow, green and blue boundaries as we can see in Figure 6. The left and the right panels of Figure 6, clearly shows the spatial variation of R and Z distribution respectively.

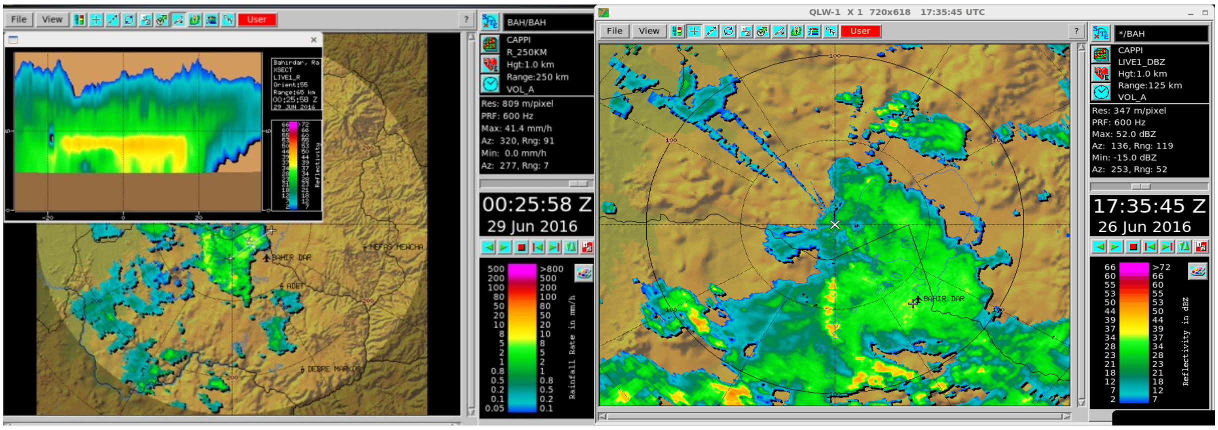

Figure 6. R in (mm/h) and Z (dBZ) distribution.

The left panel of Figure 6 indicated that the movement of clouds in the atmosphere. In this figure we can easily predict rainfall for a short period forecasting. Radar observation is unique from satellite and gauge observation, because it shows the rain droplets at some cloud level before reaches the ground and it tells the potential of the cloud that reaches the maximum thermodynamics points. The cross-section region of the clouds the yellow colors in Figure 6 is marked by Z is equal to 40 dBZ and D_0 is greater than 1.2 mm. The green part of the cross-section region is marked by considerably the Z value is less than 40 dBZ and D_0 is proximity 0.5 mm. The blue parts of the cross region is marked by very less value of Z and we couldn`t to determine $D_0$ from irregular shape of rain droplets. Because, the cloud is full of moistures but not have full rain droplets. It couldn`t reach the maximum thermodynamics points as shown the left panel of Figure 6. The radar profile shows the structure of the clouds refer the left panel of Figure 6.

CONCLUSION AND RECOMMENDATION

This paper showed as weather radar rainfall estimates by developing the Z-R relation model for the first time in Ethiopia using Z and R data independently. It is quite useful for meteorologists and hydrologists to extract rainfall data with a required spatial and temporal resolution. The components of 'a' and 'b' parameters derived from this study is found to be 50 and 1.02 respectively. Rainfall is showed as very dynamical temporally and spatial variability in the atmosphere. Convective rain type is dominated for the study area and for the study period. R from empirical Z-R relation model and the gauge direct observation were well fitting as developed in this paper. There is a less variation on the deviations between the radar empirical Z-R relation model and the gauge direct observation. Z-R relationships should be valid in the radar system according to the climatic seasons in Ethiopia. The outcomes from this study will be considered for future configuration and calibration of the radar system in Ethiopia. This study has been carryout as guidance to perform future research by weather radar rainfall estimation errors in Ethiopia.

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