

A Comparative Study for the Estimation of Downward Longwave Radiation under Clear Sky Condition across the Midland Climatic Zone of Nigeria

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ABSTRACT

Downward Longwave Radiation (DLR) is a crucial component of the Earth's surface radiation budget, important for both local weather forecasting and global climate modeling. This study investigates the clear-sky DLR in Minna and Zaria, with the aim at comparing and estimating the DLR under a cloudless sky for the region. The specific objectives include examining the influence of DLR on relative humidity and air temperature, evaluating the performance of eleven widely used existing empirical models, developing five new locally calibrated regression models, and ranking all sixteen models to ascertain their reliability and applicability in the study area. Monthly average daily meteorological data of relative humidity, air temperature, and DLR, spanning a forty-year period (1984–2023) were utilized for the study. Model performance was assessed using five statistical indicators: Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t-test, and Index of Agreement (IA), supplemented by correlation coefficient (R) for the proposed modified models. For Minna, maximum DLR of 424.7500 Wm^{-2} was recorded in April, while the minimum of 360.6771 Wm^{-2} occurred in December. At Zaria, the peak DLR of 412.0104 Wm^{-2} was observed in May, with the lowest value of 333.6875 Wm^{-2} recorded in December. Among the eleven existing models evaluated, the Idso model ranked best for both Minna and Zaria with overall ranking scores of 12 and 5 respectively, while the Dillely and O'Brien model performed least. Among the five newly developed modified regression models, the modified Idso model proved most accurate for Minna, and the modified Guest model was found most suitable for Zaria. Generally, the developed modified DLR models outperformed the existing models, which can be recommended for the estimation of DLR for midland climatic zone in the absence of the measured DLR.

Keywords:

Clear-sky condition,
Downward Long wave
Radiation,
Meteorological Parameters,
Midland Climatic Zone,
Validation Test Indicators.

INTRODUCTION

The earth's climatic system is fundamentally governed by the interaction between incoming solar radiation and outgoing terrestrial radiation. The balance between these radiative fluxes determines global temperature distribution, atmospheric circulation, and the hydrological cycle. A critical component of this energy system is downward longwave radiation (DLR), defined as the infrared radiation emitted by atmospheric gases, aerosols, and clouds toward the earth surface (Stephens *et al.*, 2012). Unlike shortwave solar radiation, which depends on day light conditions is continuously emitted by the atmosphere both during daytime and nighttime. This makes it one of the most persistent contributions to

the surface energy balance (Stephens *et al.*, 2012; Wild *et al.*, 2015).

Downward longwave radiation constitutes a fundamental part of the net radiation balance at the earth's surface. By approximating the atmosphere as a grey body, the DLR flux can be formulated in terms of an effective atmospheric emissivity (ϵ_A) and near-surface air temperature (T_A) (Prata, 1996; Guo *et al.*, 2018).

$$L \downarrow = \epsilon_A \sigma T_A^4 \quad (1)$$

Where σ represents the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$) (Prata, 1996; Guo *et al.*, 2018). The atmospheric emissivity ϵ_A is dimensionless, whereas DLR ($L \downarrow$) is measured in Wm^{-2} and air temperature (T_A) in Kelvin. This formulation suggests

that, under clear-sky conditions, atmospheric emissivity is governed by the vertical thermal structure of the atmosphere. Consequently, ε_A is commonly parameterized as a function of water-vapour pressure, air temperature, or a combination of both variables (Carmona *et al.*, 2014; Guo *et al.*, 2018).

The knowledge of DLR flux is important for estimating net radiation, analyzing the surface energy balance, studying climatic change and designing radiant cooling systems (Crawford and Duchon, 1999; Arya, 2001; Gröbner *et al.*, 2009; Carmona *et al.*, 2014). However, observations of this flux are often unavailable at many meteorological stations because of technical challenges and the high cost of purchasing and maintaining the pyrgeometers used for its measurement. Despite its importance, high-quality, long-term ground-based measurements of DLR are relatively rare compared to solar radiation measurements. As a result, many researchers have developed empirical models to estimate DLR at the earth's surface under clear-sky conditions using commonly available meteorological variables such as relative humidity, water vapour pressure and air temperature (Crawford and Duchon, 1999; Kruk *et al.*, 2010).

The earliest empirical relationship for estimating DLR under a clear-sky condition based on Equation (1), was proposed by Ångström in 1929. Since then, many researchers have introduced additional empirical formulations, including those developed by Swinbank (1963), Idso and Jackson (1969), Deacon (1970), Brutsaert (1975), Idso (1981), Garratt (1992), Prata (1996), Dille and O'Brien (1998), and Guest (1998). These models have subsequently been applied in different climatic environment and locations to parameterize DLR flux under varying atmospheric conditions (Carmona *et al.*, 2014; Guo *et al.*, 2018). The application of all the developed empirical models to parameterize the flux at both the regional and global scales are unknown. In this regard, there is need to carry out an investigation to find out if this universally accepted models are very suitable for estimation of DLR in all regions in Nigeria. The quest for the most suitable models for estimating DLR necessitated the need to develop new models. This study is aimed at comparing and estimating the DLR radiation under a cloudless sky in Minna and Zaria located across the Midland climatic zones with the objectives outlined as follows (i) To access the performance of the existing widely used empirical DLR models (ii) To develop and compare five (5) new DLR models for Minna and Zaria (iii) To rank the eleven (11) existing DLR models and the five (5) modified newly developed DLR models to ascertain which reliably estimate DLR in the midland zone (iv) To compare the models through the different validation indicators to ascertain the suitability and applicability of

the models (v) To investigate the impact of DLR on relative humidity and temperature in the midland zone.

MATERIALS AND METHODS

Acquisition of Data

According to the World Meteorological organization (2017), also in Ojo and Adeyemi (2014) mentioned that reliable climate modelling requires data records extending for at least thirty (30) years or more. Consistent with this recommendation, the monthly average daily data for relative humidity, air temperature and DLR employed in this study covers a forty (40) years (1984-2023) period and were sourced from the National Aeronautics and Space Administration (NASA). Thirty-two (32) (1984-2015) years data was used to develop the DLR based empirical models while eight (8) years (2016-2023) data was used for the validation of the models. This study employed the same approach adopted by Soneye-Arogundade (2021); Akpootu and Abdullahi (2022), and Akpootu *et al.* (2022) where approximately 80 % of the total years of the data were used for the development of models and 20 % for validation of models. The locations under investigation are Minna (Latitude 9.60 °N and Longitude 6.55 °E) and Zaria (Latitude 11.09 °N and Longitude 7.72 °E) located across the Midland climatic zones of Nigeria.

Clear-Sky Downward Longwave Radiation Models

Eleven (11) previously published empirical models were applied to estimate the downward longwave radiation flux under clear sky conditions. The existing models are presented below:

(1) Ångström (1929) estimated longwave irradiance from air temperature and water vapor pressure with an equation of the form:

$$L_{\downarrow cl} = (0.83 - 0.18 \times 10^{-0.067e_0}) \sigma T_A^4 \quad (2)$$

$L_{\downarrow cl}$ is the atmospheric longwave irradiance

Where e_0 water is vapor in hectopascals (hPa) and is given by:

$$e_0 = \frac{RH}{100} \left\{ 1.33322368 \left[\exp \left(\frac{20.386 - 5132}{T_A} \right) \right] \right\}$$

$$\sigma = \text{Stefan Boltzmann constant } (5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4})$$

Where RH is the relative humidity in percentage; and T_A is the air temperature.

(2) Swinbank (1963) developed an equation for estimating downward longwave atmospheric irradiance that only depended on screen-level air temperature. It is given by the expression:

$$L_{\downarrow} = (0.94 \times 10^{-5} T_A^2) \sigma T_A^4 \quad (3)$$

(3) Idso and Jackson (1969) estimated longwave irradiance from air temperature which is given by the expression:

$$L_{\downarrow} = \{1 - 0.261 \exp[-7.77 \times 10^{-4} (273 - T_A)]\}^2 \sigma T_A^4 \quad (4)$$

(4) Deacon (1970) equation estimated longwave atmospheric irradiance from air temperature and altitude as:

$$L_{\downarrow cl} = (0.94 \times 10^{-5} T_A^2) - \left[0.035 \left(\frac{z}{1000}\right)\right] \sigma T_A^4 \quad (5)$$

Where z is the altitude of the meteorological sites in meters

(5) Brutsaert (1975) proposed an equation in which emissivity is a function of water vapor pressure and temperature. It is given by the expression:

$$L_{\downarrow cl} = 0.643 \left(\frac{e_0}{T_A}\right)^{\frac{1}{7}} \sigma T_A^4 \quad (6)$$

(6) Idso (1981) estimated longwave irradiance from air temperature and water vapor pressure with an equation of the form:

$$L_{\downarrow cl} = [0.7 + 5.95 \times 10^{-7} e_0 \exp(1500/T_A)] \sigma T_A^4 \quad (7)$$

(7) Garratt (1992) estimated longwave irradiance from air temperature and water vapor pressure with an equation of the form:

$$L_{\downarrow cl} = [0.79 - 0.174 \exp(-0.095 e_0)] \sigma T_A^4 \quad (8)$$

(8) Prata (1996) proposed an equation in which emissivity is a function of precipitable water and temperature. It is given by the expression:

$$L_{\downarrow cl} = (1 - [(1 + w) \exp(-1.2 + 3.0w)^{0.5}]) \sigma T_A^4 \quad (9)$$

Where w is the precipitable water content in kgm^{-2} and $w = 0.465(e_0/T_A)$

(9) Dillely and O'Brien (1998) proposed an equation in which emissivity is a function of precipitable water and temperature at screen level. It is given by the expression:

$$L_{\downarrow cl} = 59.38 + 113.7(T_A/273.16)^6 + 96.96 \sqrt{\frac{w}{25}} \quad (10)$$

(10) Guest (1998) estimated longwave irradiance from air temperature and relative humidity with an equation of the form:

$$L_{\downarrow cl} = \sigma T_A^4 \times 1.0438 + 0.2486 RH - 113.6 \quad (11)$$

(11) Kruk *et al.*, (2010) estimated longwave irradiance from air temperature and water vapor pressure with an equation of the form:

$$L_{\downarrow cl} = \left[0.576 \left(\frac{e_0}{T_A}\right)^{0.202}\right] \sigma T_A^4 \quad (12)$$

Validation of Models

The estimated values of the DLR obtained from the empirical models for both the existing and modified were compared with the measured DLR for Minna and Zaria by calculating the Mean Bias Error (MBE), Root Mean Square (RMSE), Mean percentage Error (MPE), t-test, Index of Agreement (IA) while the correlation coefficient (R) for the proposed modified models was determined from Minitab computer software and origin software was employed to plot the correlation graphs. The MBE, RMSE, and MPE were calculated using the equations as

given by El-Sabaii and Trabea (2005) as reported in Olomiyesan *et al.* (2021).

$$MBE = \frac{1}{n} \sum_{i=1}^n (Et_i - Md_i) \quad (13)$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^n ((Et_i - Md_i))^2 \right]^{\frac{1}{2}} \quad (14)$$

$$MPE = \frac{1}{n} \sum_{i=1}^n \left(\frac{Md_i - Et_i}{Md_i} \right) \times 100 \quad (15)$$

In line with the explanation provided by Bevington (1969), the t test was utilized to evaluate the mean values generated by the developed models. This statistical technique is based on a parameter represented by “t,” which incorporates the degree of freedom in its computation. According to Akpootu *et al.* (2019a, b) and Akpootu *et al.* (2023), the t-test is a non-dimensional parameter and it can be mathematically expressed as follows:

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2} \right]^{\frac{1}{2}} \quad (16)$$

The location was statically tested at the (1- α) confidence levels of significance of 95% and 99%. For the critical t-value, i.e., at α level of significance and degree of freedom, the calculated t-value must be less than the critical value ($t_{critical} = 2.20, df = 11, p < 0.05$ for 95% and ($t_{critical} = 3.12, df = 11, p < 0.01$) for 99%.

The index of agreement (IA) was calculated using the below equation (Willmott, 1981)

$$IA = 1 - \frac{\sum_{i=1}^n (Et_i - Md_i)^2}{\sum_{i=1}^n (|Et_i - \bar{M}\bar{d}| + |Md_i - \bar{M}\bar{d}|)^2} \quad (17)$$

In equation (13)- (17), i represent the i^{th} observed and corresponding i^{th} predicted values of DLR, while n denotes the total number of observations. The $\bar{M}\bar{d}$ and $\bar{E}\bar{t}$ indicates the mean measured DLR and the mean estimated DLR respectively. Studies by Iqbal (1983) and Chen *et al.* (2004) indicate that an MBE value approaching zero is ideal, whereas lower RMSE and MPE value are preferred for accurate model prediction. Generally, smaller magnitudes of MBE, RMSE, MPE, and the t-statistic signify superior model performance. Positive MBE and MPE values indicate that the model tends to overestimate the calculated results, while negative values suggest underestimation. For reliable performance, the MPE should remain small, and percentage errors within the range of -10% to + 10% are considered acceptable, as reported by Merges (2006). Moreover, Akpootu *et al.* (2019a) noted that higher values of R, and IA correspond to improved model accuracy, as R and IA values approaches 1.0 (100%) reflects strong predictive agreement. In terms of measurement units, MBE and RMSE are expressed in Wm^{-2} ; MPE, R, and IA in percentage when multiply by 100, whereas t-test is dimensionless. Proposed model under a cloudless sky condition are shown in Table 1.

Table 1: DLR Based Models Proposed in this Study

Model No.	Model Type	Regression equation
1	Modified Angstrom	$L_{\downarrow cl} = (a + b \times 10^{ce_0})\sigma T^4$
2	Modified Deacon	$L_{\downarrow cl} = \left[aT_A^2 + b \left(\frac{Z}{1000} \right) \right] \sigma T^4$
3	Modified Idso	$L_{\downarrow cl} = \left(a + be_0 \exp \left(\frac{1500}{T_A} \right) \right) \sigma T^4$
4	Modified Dilley and O'Brien	$L_{\downarrow cl} = a + b \left(\frac{T_A}{273.16} \right)^6 + c \sqrt{\frac{w}{25}}$
5	Modified Guest	$L_{\downarrow cl} = [a\sigma T^4 + bRH + c]$

The proposed models which were developed through the regression analysis are modified form of the existing DLR based models. The modification of the existing models was to attest if the accuracies of the models are

improved or not through statistical validation when compared to the existing models.

RESULTS AND DISCUSSION

Statistical Analysis Summary of DLR for Minna

Table 2: Statistical Error Indicators for the Eleven Estimated DLR over Minna

Models	MBE	RMSE	MPE	t	IA
Angstrom	-30.3701	36.2728	7.1799	5.0786	0.5584
Swinbank	-25.1875	30.8694	5.9481	4.6808	0.6284
Idso & Jackson	-22.7583	28.8001	5.3547	4.2766	0.6478
Deacon	-27.9882	33.2074	6.6377	5.1941	0.6109
Brutsaert	-14.5183	16.7209	3.4596	5.8049	0.8711
Idso	9.2866	10.9636	-2.3112	5.2853	0.9509
Garratt	-48.5371	52.5135	11.6531	8.0308	0.4696
Prata	-17.1132	19.4997	4.0801	6.0720	0.8300
Dilley&O'Brien	-114.2748	115.5304	27.8995	22.3125	0.2922
Guest	-23.4762	26.8909	5.6803	5.9371	0.7332
Kruk	-9.3793	10.6991	2.2717	6.0430	0.9514

Table 2 summarized the different statistical validation test for the eleven estimated DLR models for Minna. From the above table, the existing Idso (1981) model had the lowest MBE value with an overestimation of 9.2866 Wm⁻². Kruk *et al.* (2010) had the lowest RMSE and MPE value of 10.6991 Wm⁻² and overestimation of 2.2717 % respectively. The Kruk *et al.* (2010) model equation has the highest IA value of 0.9514 (95.14 %) followed by Idso (1981) which has IA value of 0.9509 (95.09 %). In contrast, Dilley & O'Brien (1998) model has the highest

MBE, RMSE, MPE and t-statistic value of 114.2748 Wm⁻², 115.5304 Wm⁻², 27.8995% and 22.3125 respectively, exceeding all other models and indicating largest relative error and weakest model. The Idso and Jackson had the lowest t statistic value of 4.2766. The result of the existing models indicated that all the MPE values are within the acceptable range of (MPE ≤ ± 10%) apart from Garratt (1992) and Dilley and O' Brien (1998) existing models.

Table 3: Ranking of the Eleven Estimated DLR over Minna

Models	MBE	RMSE	MPE	t	IA	RANK
Angstrom	9	9	9	3	9	39
Swinbank	7	7	7	2	7	30
Idso & Jackson	5	6	5	1	6	23
Deacon	8	8	8	4	8	36
Brutsaert	3	3	3	6	3	18
Idso	1	2	2	5	2	12
Garratt	10	10	10	10	10	50
Prata	4	4	4	9	4	25
Dilley&O'Brien	11	11	11	11	11	55
Guest	6	5	6	7	5	29
Kruk	2	1	1	8	1	13

Table 3 summarized the ranks obtained from the eleven estimated DLR models over Minna. The rank obtained by each of the models varies between the value 12 and 55. Idso (1981) model, is ranked as the best overall based on the statistical accuracy assessment test particularly in its low MBE with lowest ranking value of 12 followed by Kruk *et al.* (2010) with a ranking value of 13 and Idso (1981) was found more accurate in the estimation of DLR in Minna as compared to other models. This outcome

corroborates the findings of Guo *et al.* (2018), in their comprehensive global meta-analysis of DLR parameterization models, similarly confirmed the dominance of the Idso (1981) formulation across tropical climatic environments, attributing its superiority to its exponential vapour pressure term which appropriately amplifies estimated emissivity under high humidity conditions.

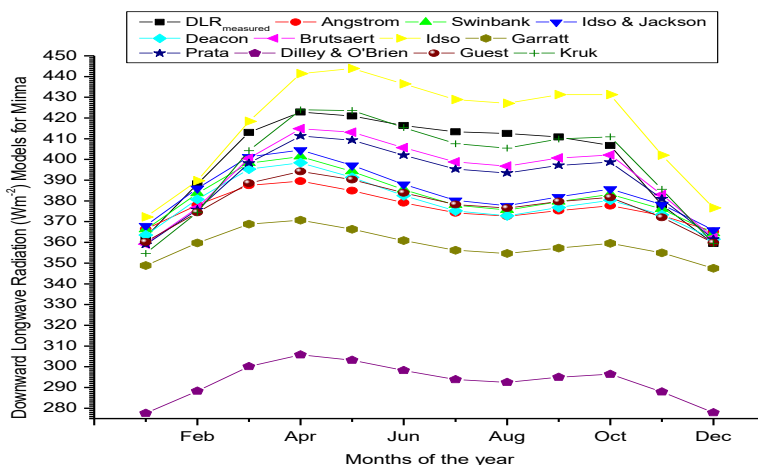


Figure 1: Variation of Measured DLR with the Eleven Estimated DLR Models over Minna

Figure1 shows the variation of measured DLR and the eleven evaluated DLR model for Minna. It was observed that the Idso (1981) model overestimated the measured DLR and other evaluated model throughout the period under investigation. However, it depicts closed values with the measured DLR from January to March. Garratt (1992) and Dilley and O’Brien (1998) consistently underestimate the measured DLR and other evaluated models throughout the months under study. The underestimation is inclined with the limited representation of atmospheric water vapor and cloud effects in this temperatures-based region. Kruk *et al.* (2010) has a comparable pattern of variation with the measured DLR and a very close patter variation especially from the month of April, June, September and December receptively with values 423.9693 Wm⁻², 415.4350 Wm⁻², 409.8582 Wm⁻² and 359.4215 Wm⁻² respectively and an average difference of 0.8212 between the measured and estimated DLR. The result aligns with the recent global studies such as Cheng *et al.* (2024), which reported that some DLR models consistently

overestimate values, especially during warmer periods when moisture and temperature interactions intensify. The Idso (1981) model relies solely on air temperature which likely leads to systematic overestimation in warm, humid conditions particularly during the peak months like April to May.

Downward Long Wave Radiation Proposed Based Models for Minna

The results of the proposed DLR regression models for Minna are shown below

$$DLR(Wm^{-2}) = 306.1 + 0.04534 \times 10^{0.067e_o} \quad (18)$$

$$DLR(Wm^{-2}) = -1360 + 0.01967 \times T^2 \quad (19)$$

$$DLR(Wm^{-2}) = 704.3 + 0.02888 \times e_o - 2.48 \exp\left(\frac{1500}{T}\right) \quad (20)$$

$$DLR(Wm^{-2}) = -46.6 + 180.3 \left(\frac{T}{273.16}\right)^6 + 351.8\sqrt{w/25} \quad (21)$$

$$DLR(Wm^{-2}) = -415.2 + 1642\sigma T^4 + 0.970 \times RH \quad (22)$$

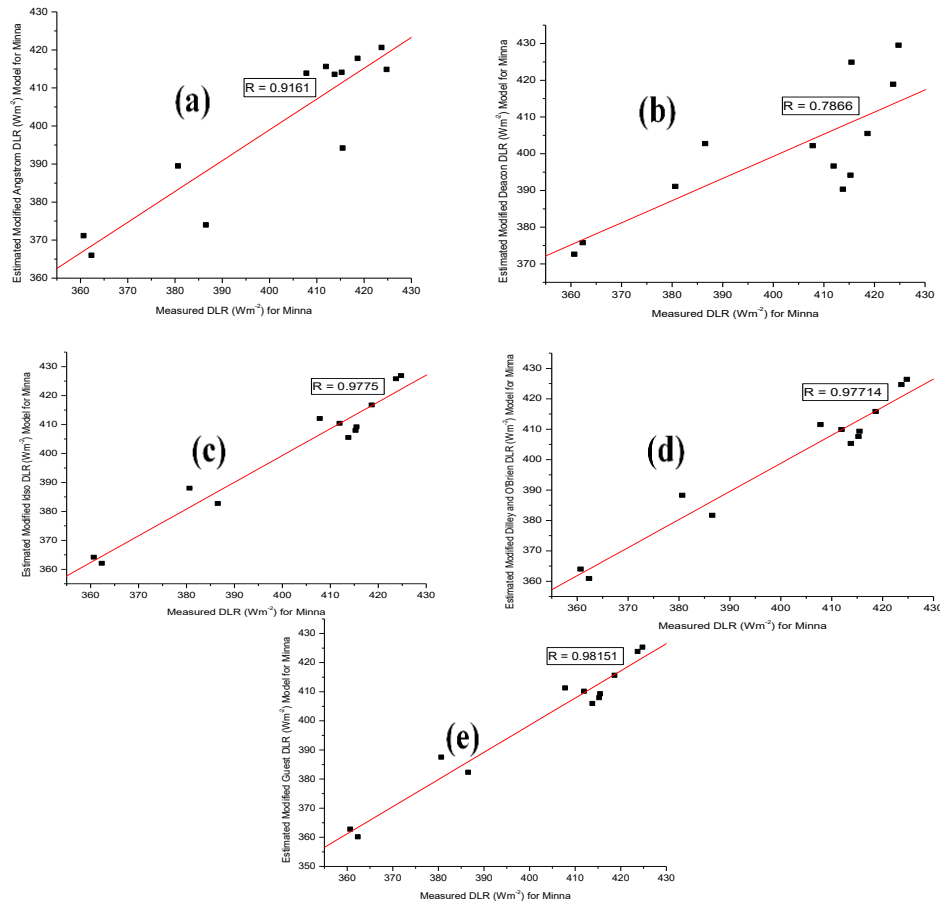


Figure 2: Correlation Coefficient of the Estimated Modified (a) Angstrom (b) Deacon (c) Idso (d) Dilley and O’Brien (e) Guest DLR Models for Minna

Figure 2 shows the correlation coefficient (R) of the estimated modified models for Minna which varies from 0.7866 (modified Deacon) to 0.9815 (modified Guest).

Table 4: Statistical Error Indicators for the Estimated Modified DLR Models over Minna

Models	R	MBE	RMSE	MPE	t	IA
Modified Angstrom	0.9161	-6.8914	12.0655	1.5935	2.3078	0.9283
Modified Deacon	0.7866	-6.9642	17.4407	1.5287	1.4445	0.8302
Modified Idso	0.9775	-6.3749	8.8435	1.5021	3.4495	0.9632
Modified Dilley & O’Brien	0.9771	-6.8938	9.1262	1.6307	3.8232	0.9609
Modified Guest	0.9815	-7.1434	9.20812	1.6945	4.0775	0.9605

Table 4 summarized the different statistical validation test for the estimated modified DLR models for Minna. From table 4, the modified Guest model has the highest coefficient of correlation (R) with value 0.9815 followed by the modified Idso with value 0.9775. It was observed that the modified Idso had the lowest value of MBE and MPE with underestimation of 6.2749 Wm^{-2} and overestimation of 1.50216 % respectively and also has the lowest RMSE with the value 8.8435 Wm^{-2} and modified Deacon recorded the lowest t-test value of

1.4445. Modified Idso also show the highest IA value of 0.9632 (96.32 %) which suggest that modified Idso emerges as the most reliable and accurate model for estimating DLR in the study area. The result of the modified models indicated that all the MPE values are within the acceptable range of ($MPE \leq \pm 10\%$). Similarly, the modified Ångstrom model is significant at 99% while the modified Deacon is significant at both 95% and 99% confidence level.

Table 5: Ranking of the Estimated Modified DLR Model over Minna

Models	R	MBE	RMSE	MPE	t	IA	Total
Modified Ångstrom	4	2	4	3	2	4	19
Modified Deacon	5	4	5	2	1	5	22
Modified Idso	2	1	1	1	3	1	9
Modified Dilley & O’Brien	3	3	2	4	4	2	18
Modified Guest	1	5	3	5	5	3	22

Table 5 summarized the ranks obtained from the modified DLR models over Minna. The rank obtained by each of the models varies between the value 9 and 22. The overall results for Minna, showed that the modified DLR regression model as given in equation 20 which is the modified Idso model was found more accurate for estimating DLR in Minna as compared to other model. This finding is consistent with the observation by Ojo and

Adeyemi (2014) that locally calibrated versions of models whose functional forms are physically grounded in both temperature and water vapour pressure exhibit the greatest improvement from coefficient recalibration, since both the temperature and moisture dependence of the atmospheric emissivity can be simultaneously optimized to the local climatic regime.

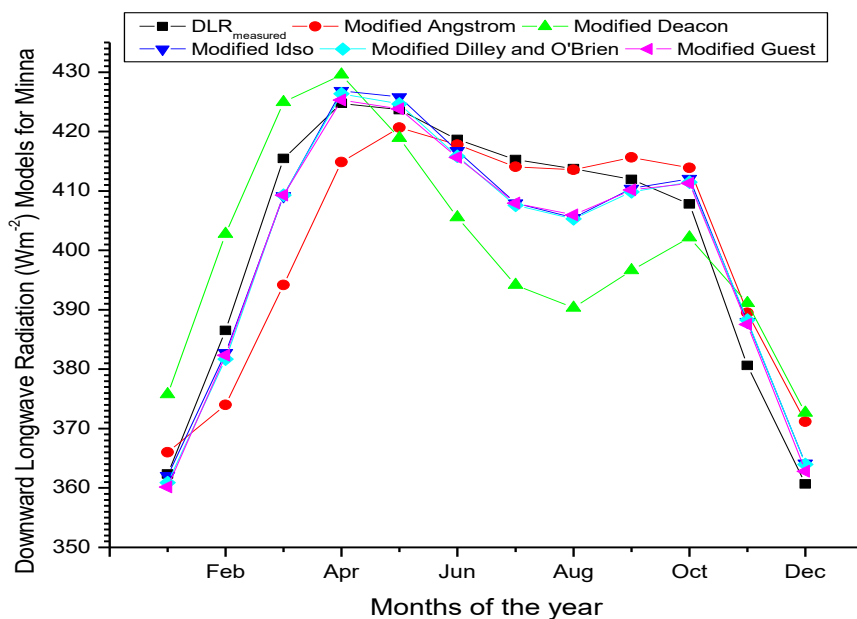


Figure 3: Variation of Measured DLR with the five Modified DLR Models over Minna

It was observed in figure 3 that the modified Deacon model overestimate the measured DLR and other evaluated model in the month of January to April and November to December with value ranging about 10 -15 Wm^{-2} and underestimated the measured and other evaluated model in the month of May to October. In contrast, the modified Ångstrom model underestimate

the measured DLR with values ranging from 3 -13 Wm^{-2} in the month of February to July. Also, the modified Idso, has a comparable pattern of variation with the measured DLR and a very close pattern variation throughout the period under investigation followed by modified Dilley and O’Brien which is the second best in ranking.

Variation of DLR with other Meteorological Parameters for Minna

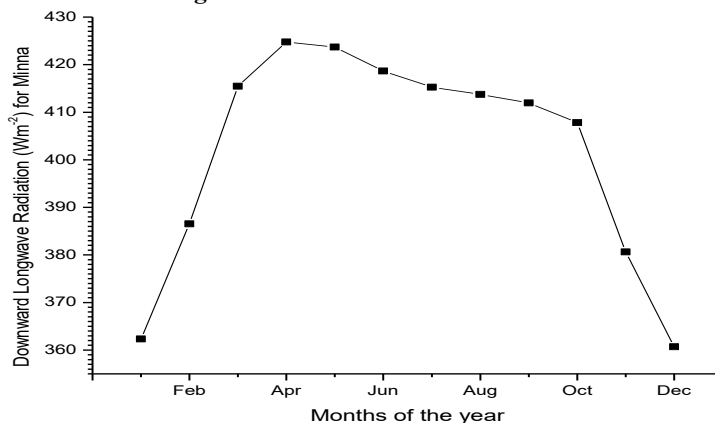


Figure 4: Monthly Variation of Measured DLR over Minna

Figure 4 shows the monthly variation of DLR for Minna. It was observed that DLR in Minna shows a gradual increase from a minimum value of 362.3229 Wm⁻² in the month of January until it gets to its peak at 424.7500 Wm⁻² in the month of April and gradually declined until it gets to 411.9375 Wm⁻² in August and significantly drops to its least value 360.6771 Wm⁻² in December. The maximum value of DLR was noticed in April with a value of 424.7500 Wm⁻² and the minimum value was noticed in month of December with a value of 360.6771 Wm⁻². The result shows that high values of DLR are observed during the rainy season with an average value of 416.5521 Wm⁻² and low values are observed during the dry season, with an average value of 381.1250 Wm⁻². This seasonal pattern of higher DLR during the rainy season driven by the combination of elevated temperature and high atmospheric water vapour content which is consistent with the findings of Ojo and Adeyemi (2014), who documented analogous seasonal DLR cycles across multiple Nigerian climatic zones, attributing the rainy season maximum to the enhancement of atmospheric emissivity by the deep, moisture-laden tropospheric

column associated with the northward advance of the Inter-Tropical Convergence Zone (ITCZ). Similar seasonal DLR behaviour has been reported by Carmona *et al.* (2014) for subtropical humid environments in South America, and by Guo *et al.* (2018) for tropical stations globally, confirming that the moisture-driven seasonal DLR maximum is a robust and geographically consistent feature of tropical and subtropical radiation climatology. The high values which were observed during the rainy season (April-October) was due to a combination of temperatures and high-water vapour. Water vapour being the dominant greenhouses gas in the atmosphere enhances the absorption and reemission of radiation. The combination of temperature and increased moisture content leads to maximum atmospheric longwave emission towards the surface leading to high values of DLR observed during this period. While the lower values in Minna were during the dry seasons (November-March) due to seasonal changes in atmospheric circulation, reductions in precipitable water vapour, even though temperatures may remain relatively high thereby reducing atmospheric emissivity leading to lower DLR.

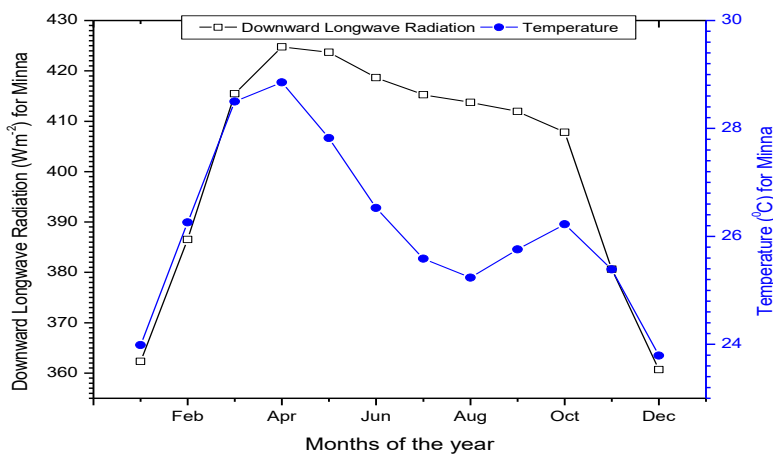


Figure 5: Monthly Variation of the Measured DLR with Temperature over Minna

Figure 5 shows the monthly variations of the measured DLR with temperature for Minna during the period of study. Clear observations show that both the measured DLR and temperature increased from the month of January and reaches its highest point with value 424.7500 Wm^{-2} and 28.8522 $^{\circ}C$ in the month of April respectively. The DLR and temperature experienced a decreased with a value of 413.7604 Wm^{-2} and 24.5743 $^{\circ}C$ respectively in the month of August. The DLR decreases from August to October while the temperature increases sharply from August to October. The DLR and temperature consequently decreases from October to December. The average value of the measured DLR during the rainy and

dry seasons are 416.5521 Wm^{-2} and 381.1250 Wm^{-2} respectively while the average value of temperature during the rainy and dry season are 26.5719 $^{\circ}C$ and 25.5841 $^{\circ}C$ respectively. This shows that the measured DLR remains relatively high during the rainy season despite the low temperatures due to increased cloud cover and atmospheric water vapour. While during the dry season, the measured DLR is low with significant increase in temperature because of low humidity and low cloud cover there by resulting in low DLR when compared to the rainy season.

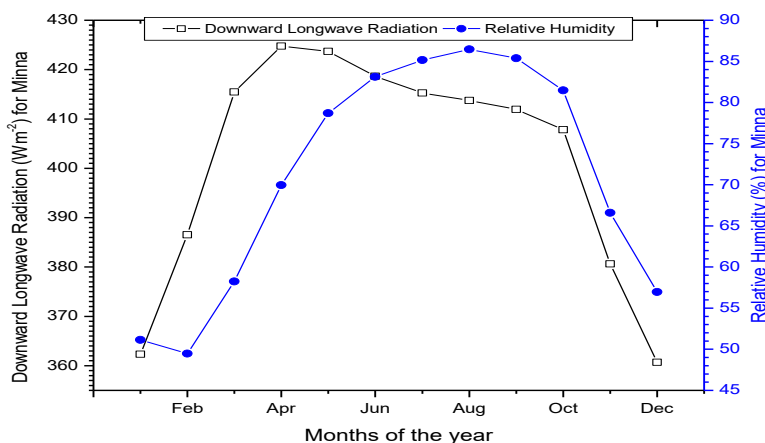


Figure 6: Monthly Variation of Measured DLR with Relative Humidity over Minna

Figure 6 shows the monthly variations of the measured DLR with RH for Minna during the period of study. The RH slightly decreased from January to February, while the DLR increases. The figure shows that both the measured DLR and RH increased from the month of February and reaches its highest point with value 424.7500 Wm^{-2} and 86.4577 % in the month of April and August respectively. The DLR and RH experienced a decreased with a value of 407.8021 Wm^{-2} and 81.4660 % respectively in the month of October. The average value of the measured DLR during the rainy and dry seasons

are 416.5521 Wm^{-2} and 381.1250 Wm^{-2} while the average value of RH during the rainy and dry season are 81.4607 % and 56.4828 % respectively, indicating that both the DLR and RH are higher during the rainy season and low during the dry season as this expected which is as result from increased atmospheric moisture boosting emissivity and longwave radiation ,and during the dry season there is an induced moisture reduction which lowers the DLR and RH as explained by the Stefan Boltzmann law.

Statistical Analysis of DLR for Zaria

Table 6: Statistical Error Indicators for the Eleven Estimated DLR over Zaria

Models	MBE	RMSE	MPE	t	IA
Angstrom	-14.0386	27.7517	3.1806	1.9449	0.6865
Swinbank	-14.4376	25.4747	3.3997	2.2814	0.7780
Idso & Jackson	-12.6612	24.2896	2.9415	2.0258	0.7940
Deacon	-24.417	32.2861	6.0408	3.8337	0.7175
Brutsaert	-15.4256	16.8390	3.9843	7.5759	0.9276
Idso	3.4671	9.7010	-0.8398	1.2691	0.9740
Garratt	-31.6688	39.9100	7.8466	4.3245	0.6205
Prata	-15.5786	17.7060	3.9604	6.1400	0.9131
Dilley & O'Brien	-100.6260	102.5769	26.2292	16.7600	0.3934
Guest	-18.2344	25.5174	4.4380	3.3879	0.7879
Kruk	-17.2458	18.9603	4.6395	7.2596	0.9272

Table 6 summarized the different statistical validation test for the eleven estimated DLR models for Zaria. From the above table, it was observed that the Idso (1981) recorded the lowest values of MBE and MPE, with a slight overestimation of 3.4671 Wm^{-2} and an underestimation of 0.8398% in its estimated values respectively. The model also shows the lowest RMSE value of 9.7010 Wm^{-2} and 1.2691 of t-statistic. Idso (1981) model showed the highest IA value of 0.9740

(97.40%), which confirms its superior predictive capability which clearly suggest that the model outperformed other empirical model over Zaria. The result also indicated that the MPE for the estimated DLR models fall within the acceptable range of $\pm 10\%$ except for Dilley & O'Brien (1998) while the t-test for Idso (1981) is statistically significance at the 95% and 99% confidence level.

Table 7: Ranking of the Eleven Estimated DLR over Zaria

Models	MBE	RMSE	MPE	t	IA	Rank
Angstrom	3	8	3	2	9	25
Swinbank	4	6	4	4	7	25
Idso & Jackson	2	5	2	3	5	17
Deacon	9	9	9	6	8	41
Brutsaert	5	2	6	10	2	25
Idso	1	1	1	1	1	5
Garratt	10	10	10	7	10	47
Prata	6	3	5	8	4	26
Dilley & O'Brien	11	11	11	11	11	55
Guest	8	7	7	5	6	33
Kruk	7	4	8	9	3	31

Table 7 summarized the ranks obtained from the eleven estimated DLR models over Zaria. The rank obtained by each of the models varies between the value 5 and 55. Idso (1981) model, is ranked as the best overall based on the statistical accuracy assessment test which is consistent across all the five test particularly in its low MBE and better t-test with lowest ranking value of 5 and

it was found more accurate in the estimation of DLR in Zaria as compared to other models. This finding is consistent with previous comparative studies of DLR models in tropical West Africa. Soneye-Arogundade (2021) found that the Idso (1981) is among the best performing model which is consistent with its top ranking in Zaria.

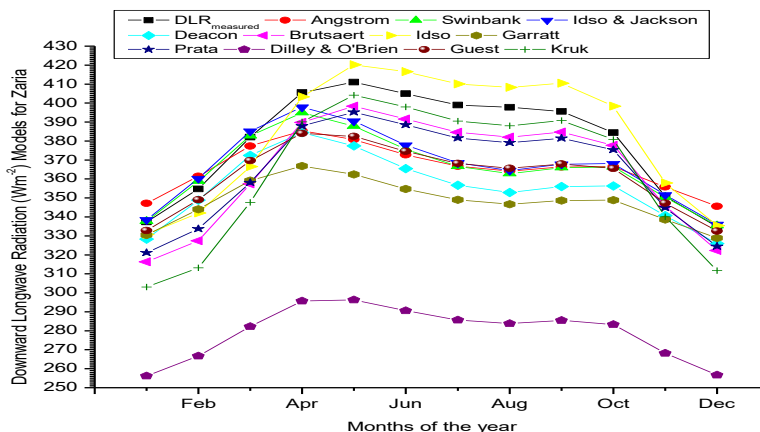


Figure 7: Variation of Measured DLR with the Eleven Estimated DLR Models over Zaria

Figure 7 shows the variation of measured DLR and the eleven evaluated DLR model for Zaria. It was observed that the Idso (1981) model overestimated the measured DLR and other evaluated model throughout the period under investigation. However, it depicts closed values with the measured DLR from January to April. Dilley and O'Brien (1998) consistently underestimate the measured

DLR and other evaluated models throughout the months under study. The underestimation is inclined with the limited representation of atmospheric water vapor and cloud effects in this temperatures-based region. Similar findings was reported by Iziomon *et al.* (2003) where they evaluated DLR models at three stations in Germany

and reported that Idso (1981) model overestimated the measured DLR under humid conditions like Zaria.

Downward Long Wave Radiation Proposed Based Models for Zaria

The result of the proposed DLR regression models for Zaria are shown below

$$DLR(Wm^{-2}) = 314.4 + 0.04182 \times 10^{-0.067ea} \quad (23)$$

$$DLR(Wm^{-2}) = -1057 + 0.01630 \times T^2 \quad (24)$$

$$DLR(Wm^{-2}) = 705.0 + 0.02295 \times e^o - 2.345 \exp\left(\frac{1500}{T}\right) \quad (25)$$

$$DLR(Wm^{-2}) = -8.9 + 186.8 \left(\frac{T}{273.16}\right)^6 + 242.4 \sqrt{w/25} \quad (26)$$

$$DLR(Wm^{-2}) = -277.9 + 1.3963\sigma T^4 + 0.6933 \times RH \quad (27)$$

Figure 8 shows the coefficient of correlation (R) for Zaria which varies from 0.8694 (modified Deacon) to 0.9926 (modified Guest)

Table 8: Statistical Error Indicators for the Estimated Modified DLR Models over Zaria

Model	R	MBE	RMSE	MPE	t	IA
Modified Angstrom	0.8747	0.0262	14.5500	-0.2760	0.0060	0.9292
Modified Deacon	0.8694	0.0858	14.2830	-0.1790	0.0199	0.9161
Modified Idso	0.9914	-0.0340	7.8708	-0.1410	0.0144	0.9820
Modified Dilley & O'Brien	0.9901	0.0531	8.2103	-0.1680	0.0214	0.9804
Modified Guest	0.9926	-0.0310	7.8093	-0.1410	0.0130	0.9823

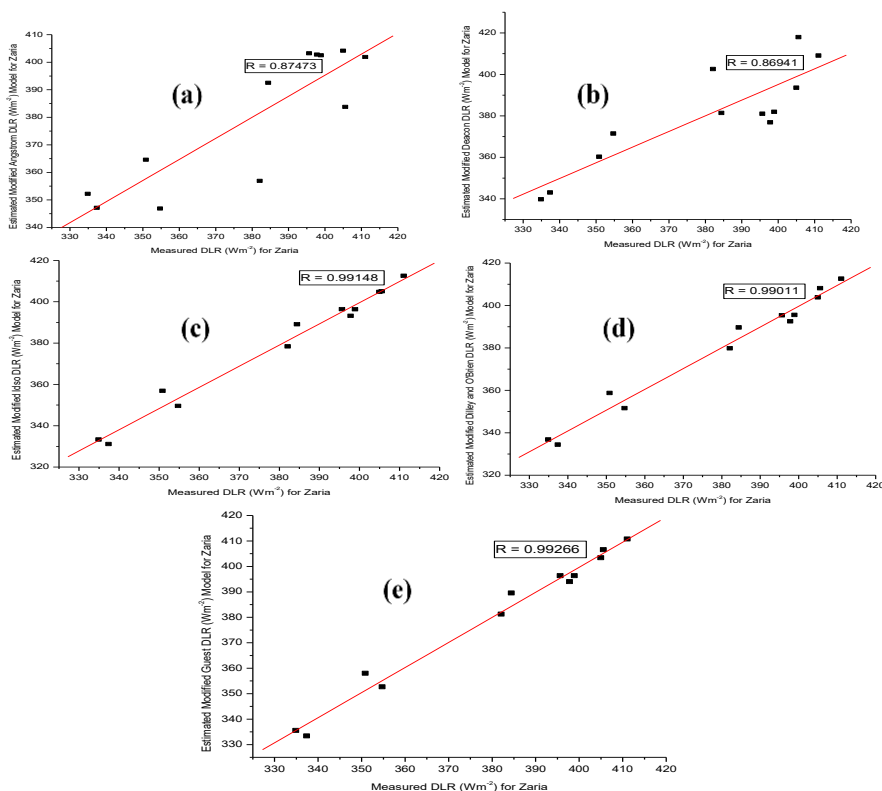


Figure 8: Correlation coefficient of the Estimated Modified (a) Angstrom (b) Deacon (c) Idso (d) Dilley and O'Brien (e) Guest DLR Models for Zaria

Figure 8 shows the coefficient of correlation (R) for Zaria which varies from 0.8694 (modified Deacon) to 0.9926 (modified Guest)

Table 8 summarized the different statistical validation test for the estimated modified DLR models for Zaria. From the table, the modified Guest model has the highest correlation of coefficient with value 0.9926. It was

observed that the modified Ångstrom had the lowest value of MBE and modified Idso and Guest has the same low value of MPE with overestimation of 0.0262 Wm⁻² and underestimation of 0.1410 % respectively and the modified Guest also has the lowest RMSE with the value 7.8093 Wm⁻² and modified Ångstrom recorded the lowest t-test with the value 0.0060. Modified Guest also

show the highest IA value of 0.9823 (98.23%). The result of the modified models indicated that all the MPE values are within the acceptable range of ($MPE \leq \pm 10\%$). Similarly, the calculated t-test value is significantly at 95 % and 99 % confidence level respectively. This finding is consistent with the acceptability benchmarks established by Merges (2006) and Iqbal (1983) and confirms that all five modified regression models developed for Zaria possess the statistical reliability required for operational deployment in surface radiation

estimation applications. The substantially higher accuracy of the modified Guest model at Zaria compared to the modified Idso model, which was the best-performing modified model at Zaria, further affirms the site-specific nature of DLR model performance documented by Carmona *et al.* (2014), and Guo *et al.* (2018), who all emphasized that no single DLR parameterization formulation achieves universally optimal performance across diverse climatic environments without local recalibration.

Table 9: Ranking of the eleven estimated DLR over Zaria

Models	R	MBE	RMSE	MPE	t	IA	Total
Modified Angstrom	4	1	5	4	1	4	19
Modified Deacon	5	5	4	3	4	5	26
Modified Idso	2	3	2	1	3	2	13
Modified Dilley and O'Brien	3	4	3	2	5	3	20
Modified Guest	1	2	1	1	2	1	8

Table 9 summarized the ranks obtained from the modified DLR models over Zaria. The rank obtained by each of the models varies between the value 8 and 26. The overall results for Zaria, showed that the modified

DLR regression model as given in equation 27 which is the modified Guest DLR model was found more accurate for estimating DLR in Zaria as compared to other model.

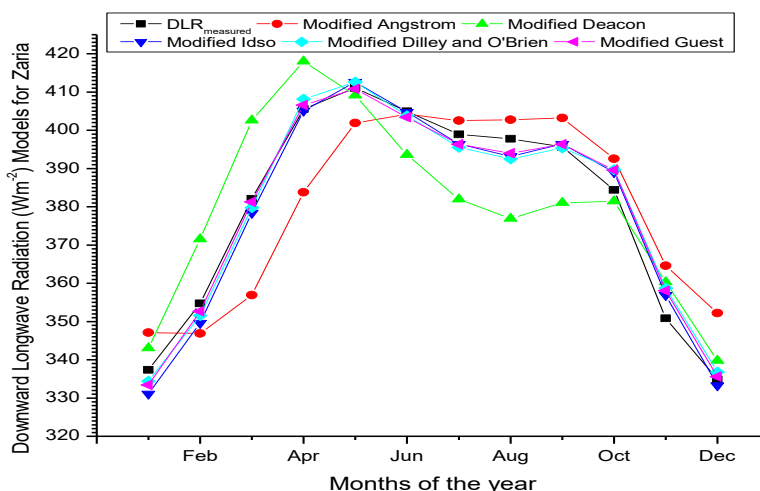


Figure 9: Variation of Measured DLR with the five Modified DLR Models over Zaria

It was observed in figure 9 that the modified Deacon model overestimate the measured DLR and other evaluated model in the month of January to April and November to December with value ranging about 10 -15 Wm^{-2} and underestimated the measured and other evaluated model in the month of May to October. In contrast, the modified Angstrom model underestimate

the measured DLR with values ranging from 3 -13 Wm^{-2} in the month of February to July. Also, the modified Guest, has a comparable pattern of variation with the measured DLR and a very close pattern variation throughout the period under investigation followed by modified Idso which is the second best in ranking.

Variation of DLR with other Meteorological Parameters for Zaria

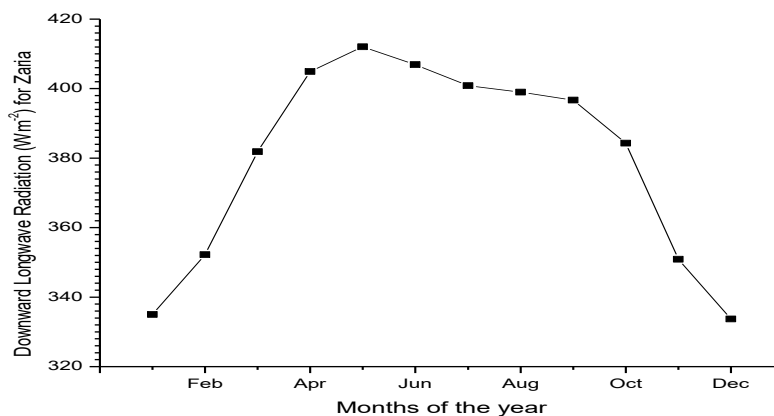


Figure 10: Monthly Variation of Measured DLR over Zaria

Figure 10 shows the variation of DLR over Zaria. It was observed that DLR in Zaria shows a gradual increase from a minimum value of 335.0208 Wm⁻² in the month of January until it gets to its peak at 412.0104 Wm⁻² in the month of May and gradually declined until it gets to 396.7188 Wm⁻² in September and significantly drops to 333.6875 Wm⁻² in December. The maximum value of DLR was noticed in May with a value of 412.0104 Wm⁻² during the rainy season and the minimum value was noticed in month of December with a value of 333.6875 Wm⁻² during the dry season. The result shows that high values of DLR are observed during the rainy season with an average value of 400.6577 Wm⁻² and low values are observed during the dry season, with an average value of 350.7271 Wm⁻². The high values which were observed

during the rainy season (April-October) was due to a combination of temperatures and high-water vapour. Water vapour being the dominant greenhouse gas in the atmosphere, enhances the absorption and re emission of radiation. The combination of temperature and increased moisture content leads to maximum atmospheric longwave emission toward the surface leading to high values of DLR observed during this period. While the lower values in Zaria were during the dry seasons (November-March) due to seasonal changes in atmospheric circulation, reductions in precipitable water vapour, even though temperatures may remain relatively high thereby reducing atmospheric emissivity leading to lower DLR.

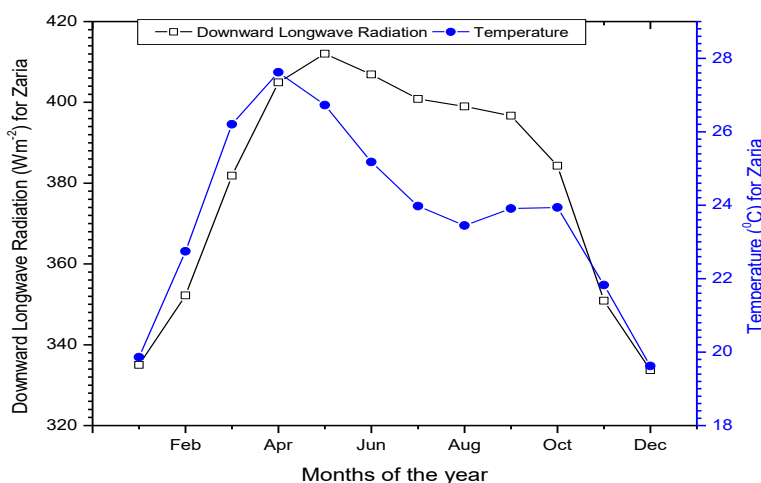


Figure 11: Monthly Variation of Measured DLR with Temperature over Zaria

Figure 11 shows the monthly variations of the measured DLR with temperature for Zaria during the period of study. Clear observations show that both the measured DLR and temperature increased from the month of January and reaches its highest point with value 412.0104

Wm⁻² and 27.6210 °C in the month of May and April respectively. The DLR and temperature experienced a decrease with a value of 396.7188 Wm⁻² and 23.4480 °C in the month of September and August respectively. The average value of the measured DLR during the rainy and

dry seasons are 400.6577 Wm^{-2} and 350.7271 Wm^{-2} while the average value of temperature during the rainy and dry season are $24.9695 \text{ }^\circ\text{C}$ and $22.0515 \text{ }^\circ\text{C}$ respectively. This shows that DLR is high with increase in temperature during the rainy season and low with

decreased in temperature during the dry season for the location under investigation explained by Stefan-Boltzman law.

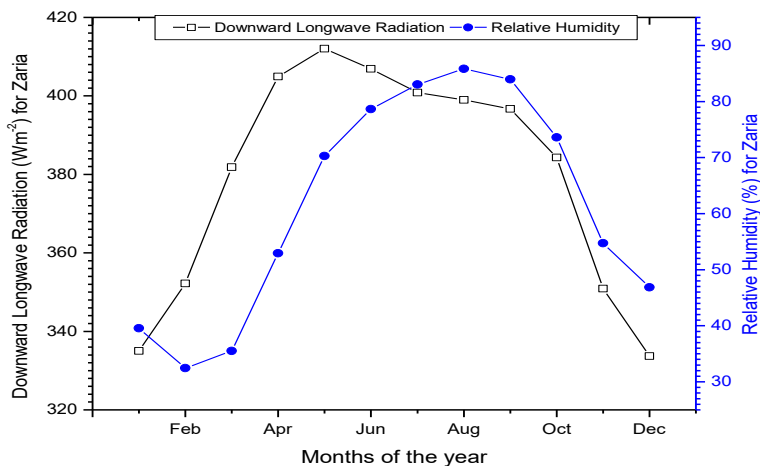


Figure 12: Monthly Variation of Measured DLR with RH over Zaria

Figure 12 shows the monthly variations of the measured DLR with RH for Zaria during the period of study. The RH slightly decreased from January to February, while the DLR increased. The figure shows that both the measured DLR and RH increased from the month of February and reaches its highest point with value 412.0104 Wm^{-2} and 85.8182% in the month of May and August respectively. The DLR and RH experienced a decreased with a value of 384.2917 Wm^{-2} and 73.6097% respectively in the month of October. The average value of the measured DLR during the rainy and dry seasons are 400.6577 Wm^{-2} and 350.7172 Wm^{-2} while the average value of RH during the rainy and dry season are 75.4658% and 41.8137% respectively, indicating that the DLR and RH is high and low during the rainy season than in the dry season respectively.

CONCLUSION

Accurate and reliable empirical regression models developed from routinely observed meteorological variables offer a very important alternative for the estimation of downward longwave radiation (DLR) at any location in the absence of directly measured pyrgeometer data. In this study, eleven (11) distinctive existing clear-sky DLR empirical models and five (5) locally developed modified regression models were evaluated and compared through the statistical validation test indicators of MBE, RMSE, MPE, t-test, IA, and R. The models were subjected to a comprehensive ranking procedure to determine the suitability, reliability, and accuracy of each model for DLR estimation in Minna and Zaria located across the Midland climatic zones of

Nigeria. The results obtained in this study, revealed that the Idso (1981) model was found to be the most accurate among the eleven existing clear-sky DLR models for DLR estimation at both Minna and Zaria, recording an overall ranking score of 12 and 5 respectively; and among the five locally developed modified regression models, the modified Idso regression model and the modified Guest regression model was found to be the most reliable and accurate for DLR estimation for Minna and Zaria respectively when statically tested using the MBE, MPE, RMSE, t-statistic, IA and R. For Minna, the maximum value of 424.7500 Wm^{-2} was recorded in April during the rainy season, while the minimum value of 360.6771 Wm^{-2} was recorded in December during the dry season. At Zaria, the maximum DLR of 412.0104 Wm^{-2} was recorded in May during the rainy season, while the minimum value of 333.6875 Wm^{-2} was recorded in December during the dry season. In the both locations, it was observed that the DLR is higher with increase in temperature during the rainy season and lower with decreased in temperature during the dry season, DLR and RH are higher during the rainy season and lower during the dry season. The average values of DLR during the rainy and dry season for the two locations are: For Minna, the average value during the rainy and dry seasons were 416.5521 Wm^{-2} and 381.1250 Wm^{-2} respectively. For Zaria, the average values during the rainy and dry seasons were 400.6577 Wm^{-2} and 350.7271 Wm^{-2} respectively. Thus, indicating that DLR values are higher in Minna as compared to Zaria during the rainy and dry seasons; this could be that Minna has lower latitude compared to Zaria.

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