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Research paper

Estimation of direct normal irradiance under various sky conditions in data sparse tropical ecological zones in Nigeria

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Abstract

In this study, models for estimating direct normal irradiance (H_b) under various sky conditions in data sparse tropical ecological zones in Nigeria were fitted. The evaluated values of clearness index indicate that the prevailing sky condition in the southern tropical zones is heavily overcast while the northern zones experience partly overcast under all sky conditions. From the analyses of the influences of clearness index on H_b, it was observed that higher values of H_b were recorded in the far north zone of Sahel savannah (FNZSS) of Sokoto while lower values were registered in the far south zone of mangrove swamp of Port Harcourt revealing an increasing trend from FSZMS to FNZSS due to the trends in cloudiness and associated atmospheric moisture with the movement through the Hadley cell calculation system along the equatorial line. The regression correlation models developed from the model performance test indicates that the proposed models could be used to estimate H_b accurately between latitude 4 to 10°N, that is, mangroves swamp and Guinea savannah tropical zones in Nigeria and other locations with comparable sky conditions.

Keywords: *Decomposition Model; Equatorial Line; Direct Transmittance; Clearness Index; Extraterrestrial Solar Radiation*.

1. Introduction

Direct normal irradiance (H_b) is the component of global horizontal irradiation (H) received per unit area by a surface that is perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky. This radiometric flux is of particular interest to concentrating solar thermal installations and installations that track the position of the sun such as concentrating solar power (CSP) systems, parabolic dish, parabolic trough, Linear-Fresnel, or solar tower and concentrating photovoltaic (CPV) systems. The accurate determination and clear understanding of the H_b parameters is required for many applications such as meteorology, radiation and energy budgets, climatology, water treatment process, heating and natural lighting, agriculture, forestry, renewable energy, design and production of solar energy systems, building of renewable power plants and a good evaluation of thermal environment within building. In spite of the enormous significance of H_b, there is no standard weather station capable to measure this radiation component in Nigeria and often there is no data available in the location of interest except National Aeronautics and Space Administration (NASA) atmospheric science data [1] among others satellite radiometric agencies across the globe. To overcome these problems, different estimation models have been proposed in different locations across the globe [2-15].

Considering the great importance of the H_b in the design of solar-energy systems requiring solar radiation tracking, such as high-intensity solar cells and high-temperature heat engines, emphasis is often put on modeling the H_b component. Basically, there are two categories of H_b models available in literature: decomposition and parametric or atmospheric transmittance models. Parametric models require detailed information of atmospheric parameters or conditions such as type, amount and distribution of clouds consisting of could cover, precipitation water content, atmospheric turbidity, and sunshine fraction [3], [5-7], [11], [16-18]. On the other hand, decomposition models are used to estimate H_b from H and extraterrestrial solar radiation (H_o) data [2-3], [8-10], [14-15], [19]. Battles et al. [20] recommended decomposition models, which are based on the correlation between the clearness index and direct fraction or direct transmittance where there are no precise information or data of atmospheric turbidity coefficient, precipitable water content and cloud cover. In this research, decomposition type models employing direct transmittance at various sky conditions were used to determine the influence of cloudiness on H_b component in six tropical ecological zones in Nigeria. This will produce H_b data for a baseline for further scientific, environmental and atmospheric research without the substantial cost of the instrumentation network that would otherwise be needed.

2. Materials and methods

2.1. Acquisition of data and study area

The long term monthly mean daily direct normal irradiance (H_b), global solar radiation on the horizontal surface (H), clearness index for cloudless sky (H/H_o) for the period of 1983-2005 for the selected state capitals and locations whose tropical ecological zones, coordinates and elevations listed in Table 1 and Fig. 1 were obtained from the National Aeronautics and Space Administration (NASA) atmospheric science data center [1]. The H_b and H data measured in $kwhm^{-2}day^{-1}$ were converted to $MJm^{-2}day^{-1}$ using a factor of 3.6. The details about the study area are found in Nwokolo and Ogbulezie [21].

Table 1: States, State Capitals, Coordinates and Tropical Ecological Zones for the Selected Stations in Nigeria

States	State Capitals	Latitude (Degree North)	Longitude (Degree East)	Elevation (Meters)	Tropical Ecological Zones
Rivers	Port Harcourt	4.75	7.00	117	Mangrove Swamp
Imo	Owerri	5.485	7.035	176	Mangrove Swamp
Oyo	Ibadan	7.378	3.947	183	Tropical Rain Forest
FCT	Abuja	9.067	7.483	484	Guinea Savannah
Borno	Maiduguri	11.85	13.16	377	Sudan Savannah
Sokoto	Sokoto	13.067	5.233	331	Sahel Savannah

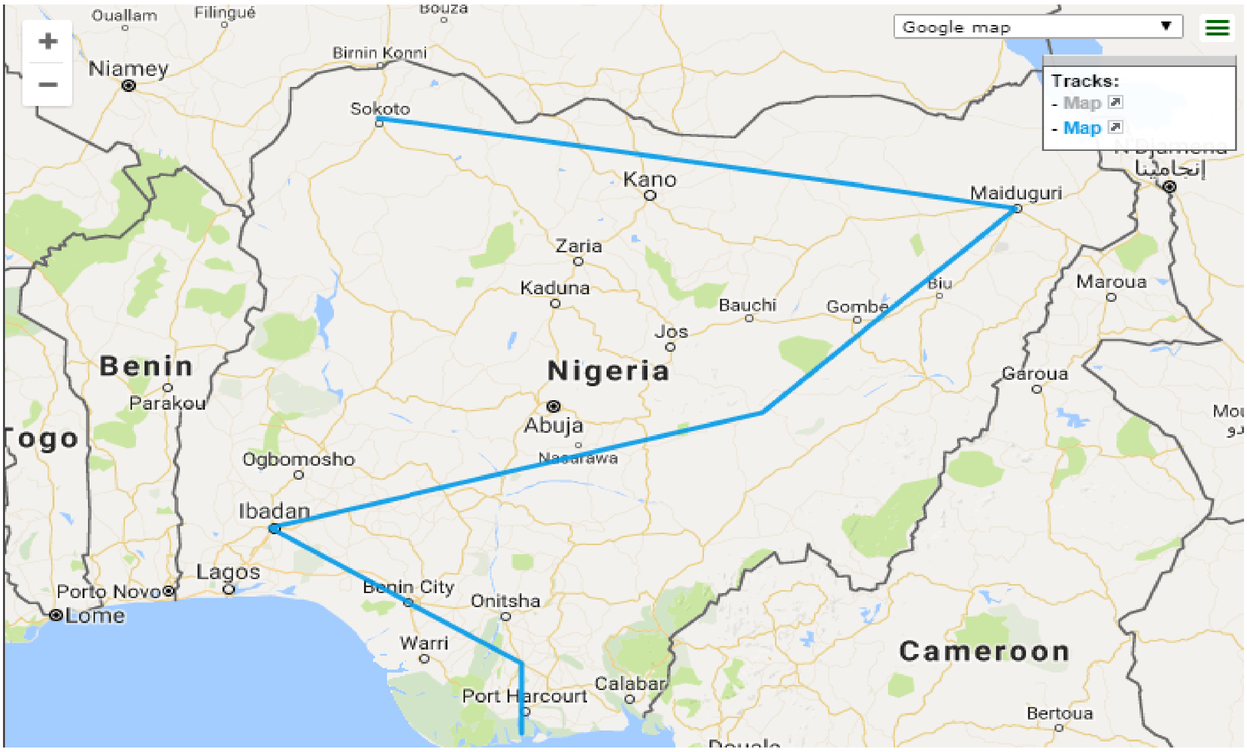

Fig. 1: Map of Nigeria Showing the Study Stations.

2.2. Model development

The modeling of H_b involves the correlation of monthly mean daily H_b to meteorological data such as extraterrestrial solar radiation (H_o) and clearness index under all sky and cloudless sky conditions. Wenxian [14] established a linear model for correlating direct transmittance to clearness index while several researchers developed quadratic models using direct transmittance to clearness index [2-3], [9-10], [15]. In order to generate an appropriate model for the study stations in addition to quadratic type model (model 1), two models based on the correlation between direct transmittance to clearness index: quadratic-exponential model (model 2) and linear-logarithmic (model 3) are proposed for all sky conditions and clear sky conditions (kt) in this research in the forms:

$$\frac{H_b}{H_o} = b_o + b_1\left(\frac{H}{H_o}\right) + b_2\left(\frac{H}{H_o}\right)^2 \quad (1)$$

$$\frac{H_b}{H_o} = b_o + b_1 \exp\left(\frac{H}{H_o}\right) + b_2 \exp\left(\frac{H}{H_o}\right)^2 \quad (2)$$

$$\frac{H_b}{H_o} = b_o + b_1\left(\frac{H}{H_o}\right) + b_2 \log\left(\frac{H}{H_o}\right) \quad (3)$$

Where bi represents the empirical coefficients, (H/H_o) is the clearness index, (H_b/H_o) represents direct transmittance and H_o representing the extraterrestrial solar radiation on the horizontal surface for all sky condition calculated using the following equations:

$$H_o = \frac{24}{\pi} I_{SC}\left(1 + 0.033\cos\frac{360n}{365}\right) \times \left(\cos\varphi\cos\delta\sin\omega_S + \frac{2\pi\omega_S}{360}\sin\varphi\sin\delta\right) \quad (4)$$

Where I_{SC} the solar constant, φ is the latitude, δ is the solar declination and n the number of days of the year starting from first January. The daily extraterrestrial solar radiation is the solar radiation intercepted by horizontal surface during a day without the atmosphere. For a given month, the solar declination (δ) and the mean sunrise hour angle (ω_S) can be evaluated by the following equations (5) and (6) respectively.

$$\delta = 23.45\sin\left[\frac{360(n+284)}{365}\right] \quad (5)$$

$$\omega_s = \cos^{-1}\left[-\tan\delta\tan\varphi\right] \quad (6)$$

A computer statistical software program (IBM SPSS 22) was used to compute the regression constants at 95% confidence level employed to obtaining the coefficient of determination (R^2).

2.3. Estimation metrics

To determine the error and performance of the predictive models, Willmott [22] suggested mean bias error (MBE) and root mean square error (RMSE) as good statistical indicator for evaluating the error between the observed and predicted (model) values. These relations are given as:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right) \quad (7)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - P_i\right)^2} \quad (8)$$

Where O_i and P_i are the observed and predicted H_b and other symbols retain their usual meaning.

3. Results and discussions

3.1. Results

The calculated values of the variation of atmospheric parameters such as extraterrestrial solar radiation (H_o), observed and predicted (models) direct normal irradiance (H_b) and clearness index for clear sky and all sky conditions in the six sites are presented in Table 2 -7 and Fig. 2 – 5. Their corresponding regression coefficients fitted and coefficient of determination employing direct transmittance and clearness index for all sky conditions and clear sky conditions are shown in Table 8, while scatter plot illustrating the observed and predicted values of H_b are shown in Fig. 6 – 11. The associated error from the fitted models were evaluated using mean bias error (MBE) and root mean square error (RMSE) in order to determine the performance of the predictive models presented in Table 9 for Port Harcourt, Owerri, Ibadan, Abuja, Maiduguri and Sokoto.

Table 2: Monthly Mean Daily Values of Extraterrestrial Solar Radiation (H_o) in $Mjm^{-2}day^{-1}$, Clearness Index (k_t) Under All Sky Conditions and Clear Sky Conditions, Observed (Obs) and Predicted (Model 1, 2 and 3) Of Direct Normal Irradiance (H_b) in $Mjm^{-2}day^{-1}$ for Port Harcourt

Month	H_o	k_t	k_t	All Conditions	All Conditions			Clear Sky Conditions		
		All Sky	Cloudless Sky	Obs H_b	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
JAN	34.52	0.54	0.53	18.68	17.97	18.34	18.19	16.01	16.05	16.03
FEB	36.40	0.52	0.53	16.81	17.93	18.29	18.22	16.82	16.86	16.85
MAR	37.66	0.46	0.55	12.82	14.00	14.32	14.42	17.43	17.47	17.46
APR	37.40	0.44	0.58	11.74	12.61	12.93	13.00	8.33	8.37	8.36
MAY	36.14	0.42	0.57	10.76	9.92	10.27	10.22	8.13	8.16	8.17
JUN	35.21	0.36	0.55	7.92	6.44	6.78	6.74	10.50	10.58	10.48
JUL	35.50	0.33	0.55	6.41	6.19	6.50	6.56	10.60	10.68	10.58
AUG	36.58	0.34	0.57	6.59	7.14	7.50	7.40	8.25	8.28	8.29
SEP	37.19	0.33	0.58	6.30	6.77	7.12	7.09	8.30	8.34	8.33
OCT	36.50	0.36	0.59	7.96	7.45	7.82	7.69	8.87	8.98	8.83
NOV	34.85	0.44	0.55	11.95	10.25	10.58	10.57	10.38	10.46	10.36
DEC	33.77	0.53	0.54	17.75	15.61	15.91	15.93	12.50	12.58	12.47
AVE	35.98	0.42	0.56	11.31	11.02	11.91	11.33	11.34	11.40	11.35
SUM	431.71	5.07	6.69	135.68	132.26	136.34	136.01	136.14	136.80	136.22

Table 3: Monthly Mean Daily Values of Extraterrestrial Solar Radiation (H_o) in $Mjm^{-2}day^{-1}$, Clearness Index (k_t) Under All Sky Conditions and Clear Sky Conditions, Observed (Obs) and Predicted (Model 1, 2 And 3) of Direct Normal Irradiance (H_b) in $Mjm^{-2}day^{-1}$ for Owerri

Month	H_o	k_t	k_t	All Conditions	All Conditions			Clear Sky Conditions		
		All Sky	Cloudless Sky	Obs H_b	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
JAN	34.09	0.58	0.54	21.19	21.44	21.47	21.37	15.63	15.67	15.63
FEB	36.11	0.56	0.52	19.33	20.16	20.12	20.20	21.33	21.37	21.34
MAR	37.55	0.51	0.55	15.84	16.80	16.74	16.90	15.13	15.17	15.15
APR	37.51	0.49	0.58	14.33	15.12	15.07	15.18	10.50	10.54	10.52
MAY	36.43	0.47	0.56	13.28	13.16	13.14	13.19	12.92	12.95	12.96
JUN	35.57	0.44	0.55	11.66	11.06	11.06	11.03	14.33	14.37	14.35
JUL	35.78	0.39	0.55	9.07	8.76	8.76	8.74	14.42	14.46	14.44
AUG	36.76	0.37	0.58	8.03	8.28	8.24	8.33	10.29	10.33	10.31
SEP	37.19	0.38	0.59	8.46	8.85	8.84	8.85	9.42	9.50	9.39
OCT	36.29	0.42	0.58	10.94	10.59	10.61	10.55	10.16	10.19	10.18
NOV	34.45	0.51	0.53	16.06	15.10	15.04	15.18	17.95	18.00	17.95
DEC	33.30	0.57	0.53	20.63	19.85	19.84	19.84	17.35	17.40	13.35
AVE	35.92	0.47	0.56	14.08	14.10	14.08	14.12	14.12	14.16	14.13
SUM	431.03	5.68	6.66	169.13	169.17	168.94	169.39	169.39	169.95	169.56

Table 4: Monthly Mean Daily Values of Extraterrestrial Solar Radiation (H_o) in $Mjm^{-2}day^{-1}$, Clearness Index (k_t) Under All Sky Conditions and Clear Sky Conditions, Observed (Obs) and Predicted (Model 1, 2 And 3) of Direct Normal Irradiance (H_b) in $Mjm^{-2}day^{-1}$ for Ibadan

Month	H_o	k_t	k_t	All Conditions	All Conditions			Clear Sky Conditions		
		All Sky	Cloudless Sky	Obs H_b	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
JAN	33.23	0.60	0.55	22.18	22.49	22.47	22.42	16.00	15.95	16.00
FEB	35.50	0.57	0.53	20.74	21.44	21.38	21.44	19.35	19.28	19.38
MAR	37.08	0.53	0.55	18.07	18.99	18.91	19.02	17.85	17.79	17.86
APR	37.44	0.50	0.56	15.70	16.74	16.66	16.76	15.64	15.61	15.62
MAY	36.72	0.48	0.56	15.08	14.89	14.83	14.90	15.34	15.31	15.32
JUN	36.00	0.45	0.54	12.74	12.46	12.41	12.44	18.86	18.78	18.89
JUL	36.36	0.41	0.55	9.50	9.89	9.85	9.85	17.51	17.45	17.51
AUG	37.08	0.38	0.57	7.96	8.17	8.12	8.15	12.35	12.31	12.33
SEP	37.08	0.40	0.58	9.36	9.43	9.39	9.39	8.45	8.32	8.46
OCT	35.78	0.45	0.57	13.64	12.38	12.33	12.36	11.92	11.88	11.90
NOV	33.66	0.54	0.52	18.61	17.99	17.92	18.02	18.35	18.33	18.33
DEC	32.36	0.59	0.55	22.10	21.11	21.07	21.07	15.58	15.53	15.58
AVE	35.75	0.49	15.47	15.50	15.45	15.45	15.48	15.60	15.54	15.60
SUM	428.29	5.90	6.63	185.69	185.96	185.34	185.81	187.18	186.52	187.18

Table 5: Monthly Mean Daily Values of Extraterrestrial Solar Radiation (H_o) in $Mjm^{-2}day^{-1}$, Clearness Index (k_t) Under All Sky Conditions and Clear Sky Conditions, Observed (Obs) and Predicted (Model 1, 2 and 3) of Direct Normal Irradiance (H_b) in $Mjm^{-2}day^{-1}$ for Abuja

Month	H_o	k_t	k_t	All Conditions	All Conditions			Clear Sky Conditions		
		All Sky	Cloudless Sky	Obs H_b	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
JAN	32.00	0.66	0.59	26.32	26.01	26.11	25.62	19.63	17.95	18.51
FEB	34.85	0.63	0.57	24.26	24.83	24.67	24.63	13.67	16.18	14.57
MAR	37.08	0.61	0.57	22.57	24.24	23.98	24.13	14.55	17.22	15.51
APR	37.91	0.58	0.59	19.94	21.47	21.12	21.46	23.26	21.26	21.93
MAY	37.44	0.54	0.57	17.71	17.83	17.49	17.88	14.69	17.39	15.66
JUN	36.86	0.49	0.56	15.19	14.51	14.22	14.63	10.02	18.55	12.22
JUL	36.97	0.43	0.57	11.48	11.16	10.89	11.61	14.51	17.17	15.46
AUG	37.37	0.40	0.59	9.68	10.12	9.79	10.93	22.92	20.96	21.62
SEP	37.04	0.46	0.58	12.60	12.53	12.27	12.78	18.75	17.89	18.54
OCT	35.32	0.54	0.56	17.86	17.18	16.86	17.22	9.60	17.77	11.71
NOV	32.83	0.66	0.60	26.21	26.08	26.12	25.72	23.44	22.98	21.41
DEC	31.39	0.67	0.61	27.54	26.08	26.82	26.14	25.36	28.33	22.67
AVE	35.59	0.56	0.58	19.28	19.38	19.20	19.40	17.53	19.47	17.48
SUM	427.07	6.67	6.96	231.37	232.56	230.35	232.74	210.40	233.66	209.81

Table 6: Monthly Mean Daily Values of Extraterrestrial Solar Radiation (H_o) in $Mjm^{-2}day^{-1}$, Clearness Index (k_t) Under All Sky Conditions and Clear Sky Conditions, Observed (Obs) and Predicted (Model 1, 2 and 3) of Direct Normal Irradiance (H_b) in $Mjm^{-2}day^{-1}$ for Maiduguri

Month	H_o	k_t	k_t	All Conditions	All Conditions			Clear Sky Conditions		
		All Sky	Cloudless Sky	Obs H_b	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
JAN	31.39	0.64	0.59	25.56	23.59	23.56	23.53	23.19	23.26	23.22
FEB	34.16	0.66	0.60	27.04	27.89	27.90	27.37	26.97	27.13	26.93
MAR	36.79	0.66	0.61	26.24	29.06	29.04	28.71	29.04	29.22	29.00
APR	38.02	0.63	0.60	23.76	26.69	26.66	26.94	27.13	27.17	27.19
MAY	37.87	0.06	0.60	23.87	24.17	24.20	24.75	24.22	24.16	24.32
JUN	37.44	0.57	0.59	20.47	20.88	21.06	21.67	21.22	21.11	21.29
JUL	37.48	0.52	0.58	16.78	16.40	16.93	16.98	16.81	16.72	16.71
AUG	37.62	0.49	0.57	14.51	14.27	15.02	14.43	14.27	14.25	13.99
SEP	36.90	0.54	0.57	17.82	17.89	18.26	18.63	18.28	18.17	18.27
OCT	34.78	0.61	0.59	22.68	22.70	22.71	23.17	23.10	23.06	23.18
NOV	31.97	0.66	0.61	26.42	25.46	25.45	25.11	25.23	25.39	25.20
DEC	30.38	0.63	0.58	24.73	21.96	21.93	22.06	21.69	21.72	21.73
AVE	35.40	0.60	0.59	22.49	22.49	22.73	22.78	22.60	22.61	22.59
SUM	424.80	7.23	7.09	269.86	270.96	272.73	273.35	271.15	271.38	271.92

Table 7: Monthly Mean Daily Values of Extraterrestrial Solar Radiation (H_o) in $Mjm^{-2}day^{-1}$, Clearness Index (k_t) Under All Sky Conditions and Clear Sky Conditions, Observed (Obs) and Predicted (Model 1, 2 and 3) of Direct Normal Irradiance (H_b) in $Mjm^{-2}day^{-1}$ for Sokoto

Month	H_o	k_t	k_t	All Conditions	All Conditions			Clear Sky Conditions		
		All Sky	Cloudless Sky	Obs H_b	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
JAN	30.42	0.65	0.60	25.42	22.52	22.60	22.52	20.90	21.40	20.98
FEB	33.44	0.69	0.63	28.80	28.03	27.89	27.89	24.79	24.92	24.72
MAR	36.43	0.68	0.64	27.97	29.03	2955	29.53	27.61	27.30	27.52
APR	38.09	0.68	0.64	27.61	30.73	30.65	30.62	28.87	28.54	28.77
MAY	38.30	0.66	0.63	26.86	29.57	29.59	29.53	28.39	28.54	28.32
JUN	38.02	0.65	0.64	26.64	28.78	28.84	28.76	28.81	28.49	28.72
JUL	37.94	0.59	0.62	21.85	22.91	23.37	23.07	27.49	27.92	27.43
AUG	37.84	0.55	0.60	17.93	17.63	18.56	17.77	26.10	26.61	26.10
SEP	36.72	0.59	0.59	20.92	21.70	22.19	21.86	24.69	24.99	24.71
OCT	34.16	0.64	0.60	24.34	24.29	24.45	24.34	23.57	24.03	23.57
NOV	31.07	0.67	0.62	27.07	24.72	24.68	24.65	22.50	22.86	22.46
DEC	29.34	0.64	0.60	25.02	21.49	21.58	21.51	20.24	20.64	20.24
AVE	35.15	0.64	0.62	25.04	25.17	25.33	25.57	25.34	25.52	25.30
SUM	421.78	7.69	7.41	300.42	302.02	303.96	302.03	304.07	306.21	303.54

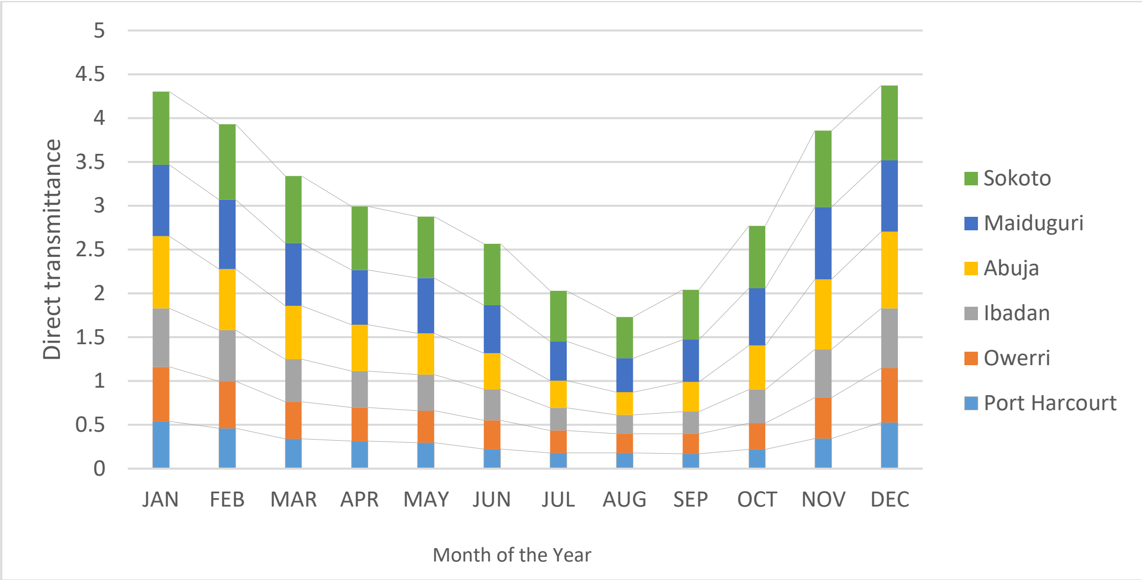

Fig. 2: Variation of Direct Transmittance for Studied Meteorological Stations.

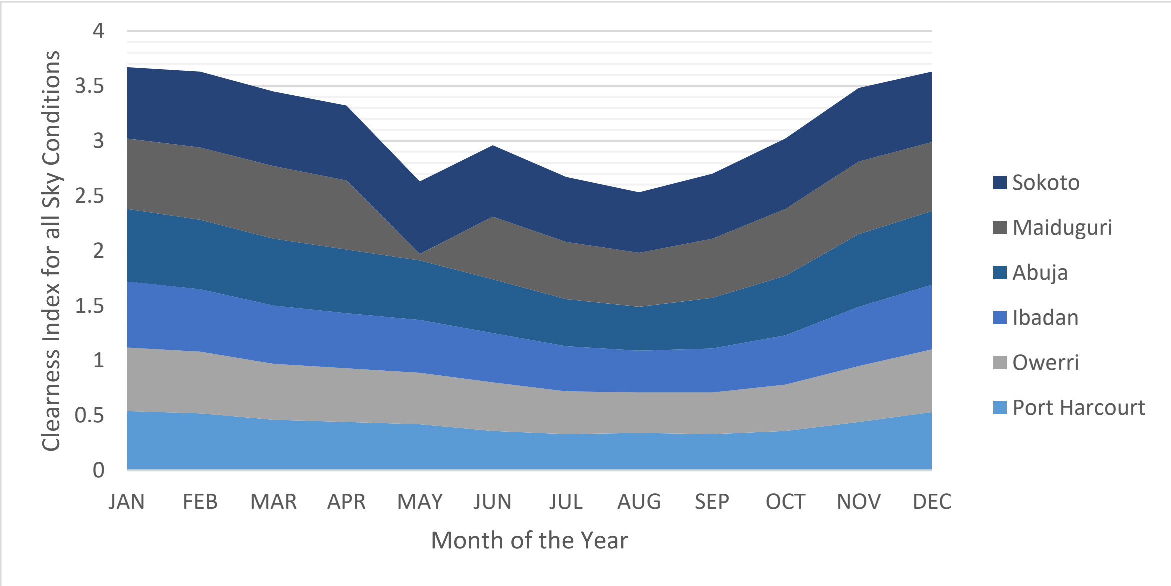

Fig. 3: Variation of Clearness Index under All Sky Conditions for Studied Meteorological Stations.

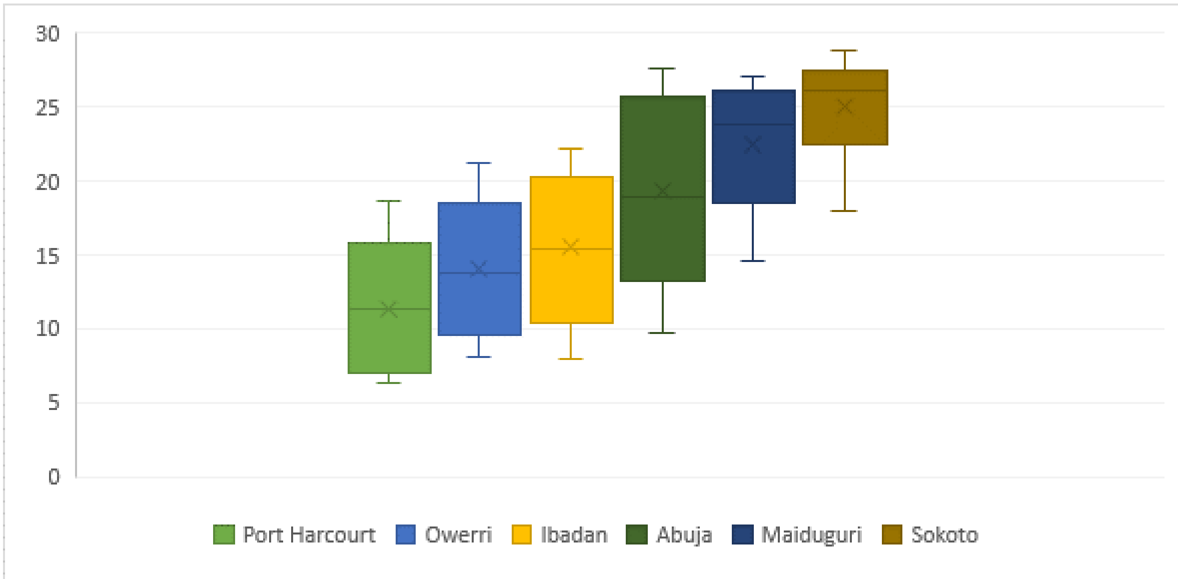

Fig. 4: Boxplot Diagram of the Variation of Direct Normal Irradiance for the Studied Meteorological Stations.

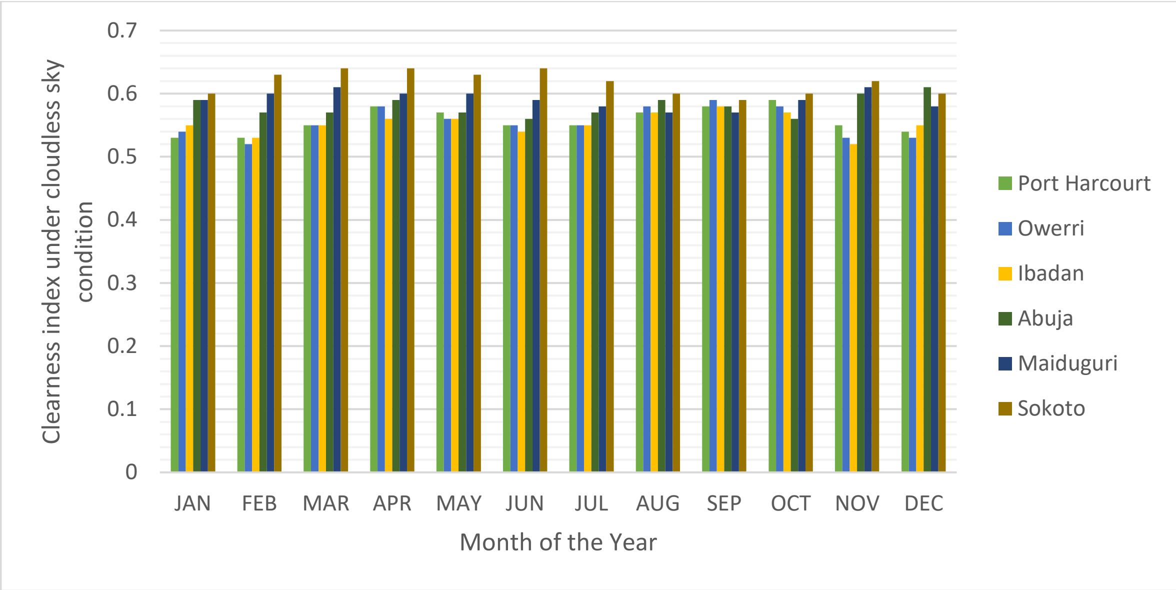

Fig. 5: Variation of Clearness Index under Cloudless Sky Conditions for the Studied Meteorological Stations.

Table 8: Statistical Results for the Validation of the of Predicted (Model) Direct Normal Irradiance (DNI) in Terms of their Capability For Estimating The Direct Normal Irradiance Under Various Sky Conditions for Port Harcourt, Owerri, Ibadan, Abuja, Maiduguri and Sokoto

Stations	Models	Sky Conditions	b_o	b_1	b_2	R^2
Port Harcourt	1	All Sky	0.289	-1.367	3.361	0.942
		Clear Sky	38.396	-132.552	115.063	0.559
	2	All Sky	-1.572	-0.616	2.362	0.941
		Clear sky	17.208	-72.460	80.321	0.559
	3	All Sky	-2.424	4.186	-164.970	0.559
		Clear sky	-110.927	124.351	-164.970	0.559
Owerri	1	All Sky	0.410	-2.005	4.075	0.984
		Clear Sky	14.140	-44.771	35.990	0.604
	2	All Sky	-1.622	-0.778	2.593	0.985
		Clear sky	9.278	-26.204	27.005	0.604
	3	All Sky	-3.578	5.592	-4.021	0.983
		Clear sky	31.350	34.210	-49.831	0.603
Ibadan	1	All Sky	-0.145	-.256	1.856	0.980
		Clear Sky	-28.675	111.330	-106.033	0.381
	2	All Sky	-1.656	0.722	0.710	0.983
		Clear sky	-28.675	111.330	-106.033	0.381
	3	All Sky	-1.984	3.744	-1.859	0.983
		Clear sky	105.560	-121.586	-1.859	0.381
Abuja	1	All Sky	0.614	-2.652	4.464	0.987
		Clear Sky	-17.142	49.800	-33.400	0.311
	2	All Sky	-1.385	-1.024	2.702	0.990
		Clear sky	38.710	-171.933	192.051	0.382
	3	All Sky	-4.810	6.881	-5.901	0.958
		Clear sky	18.262	-17.000	33.400	0.437
Maiduguri	1	All Sky	0.475	-2.222	4.122	0.896
		Clear Sky	-0.553	1.525	0.771	0.881
	2	All Sky	-1.295	0.848	2.419	0.895
		Clear sky	-1.831	1.237	0.150	0.885
	3	All Sky	-1.414	3.099	-0.0887	0.881
		Clear sky	-0.699	2.305	0.189	0.880
Sokoto	1	All Sky	-1.949	5.897	-2.692	0.719
		Clear Sky	-0.737	3.013	-1.058	0.061
	2	All Sky	-2.406	3.240	-2.000	0.719
		Clear sky	-5.488	14.697	-14.361	0.143
	3	All Sky	2.788	-1.503	5.690	0.737
		Clear sky	0.552	0.717	1.318	0.061

Table 9: Statistical Results for the Validation of the Predictive Models of Direct Normal Irradiance in Terms of Their Capability for Estimating Direct Normal Irradiance for Port Harcourt, Owerri, Ibadan, Abuja, Maiduguri and Sokoto.

Stations	Models	Sky Conditions	MBE	RMSE
Port Harcourt	1	All Sky	0.02	0.28
		Clear Sky	0.00	0.76
	2	All Sky	0.00	0.27
		Clear sky	-0.01	0.76
	3	All Sky	0.00	0.27
		Clear sky	0.00	0.76
Owerri	1	All Sky	0.00	0.15
		Clear Sky	0.00	0.72
	2	All Sky	0.00	0.15
		Clear sky	-0.01	0.72
	3	All Sky	0.00	0.16
		Clear sky	0.00	0.72
Ibadan	1	All Sky	0.00	0.17
		Clear Sky	-0.01	0.87
	2	All Sky	0.00	0.17
		Clear sky	-1.01	0.87
	3	All Sky	0.00	0.17
		Clear sky	-0.01	0.87
Abuja	1	All Sky	-010.	0.18
		Clear Sky	0.15	1.74
	2	All Sky	0.01	0.2
		Clear sky	-0.02	1.28
	3	All Sky	-0.01	0.21
		Clear sky	0.15	1.67
Maiduguri	1	All Sky	-0.01	0.35
		Clear Sky	-0.01	0.36
	2	All Sky	-0.02	0.35
		Clear sky	-0.01	0.36
	3	All Sky	-0.02	0.38
		Clear sky	-0.01	0.38
Sokoto	1	All Sky	-0.01	0.51
		Clear Sky	-0.03	1.00
	2	All Sky	-0.02	0.54
		Clear sky	-0.04	0.98
	3	All Sky	-0.01	0.52
		Clear sky	-0.02	1.00

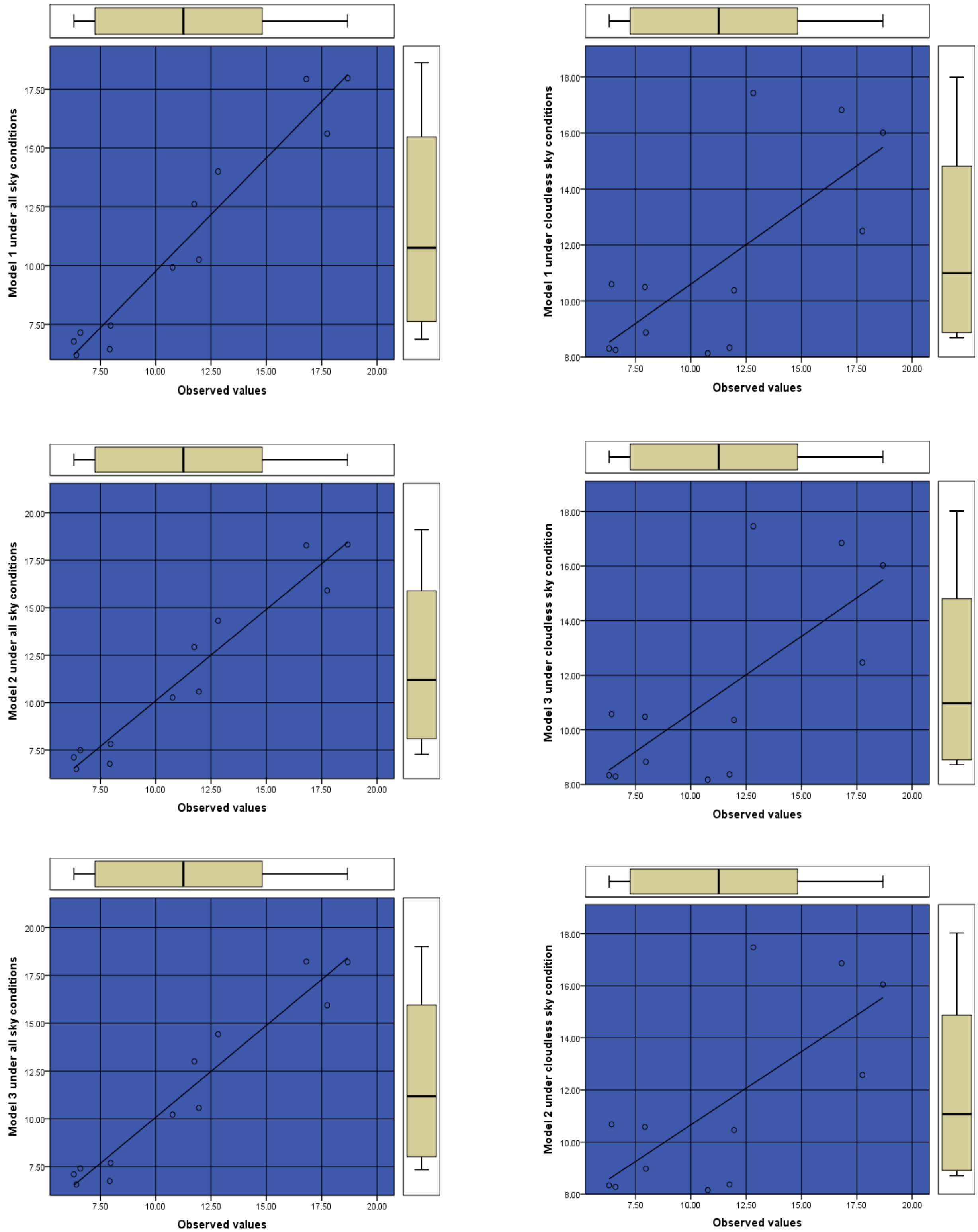

Fig. 6: Scatter Plots and Box diagrams between observed and predicted (models) direct normal irradiance under all sky condition (model 1, 2, 3) and under cloudless sky condition (model 1, 2, 3) for Port Harcourt

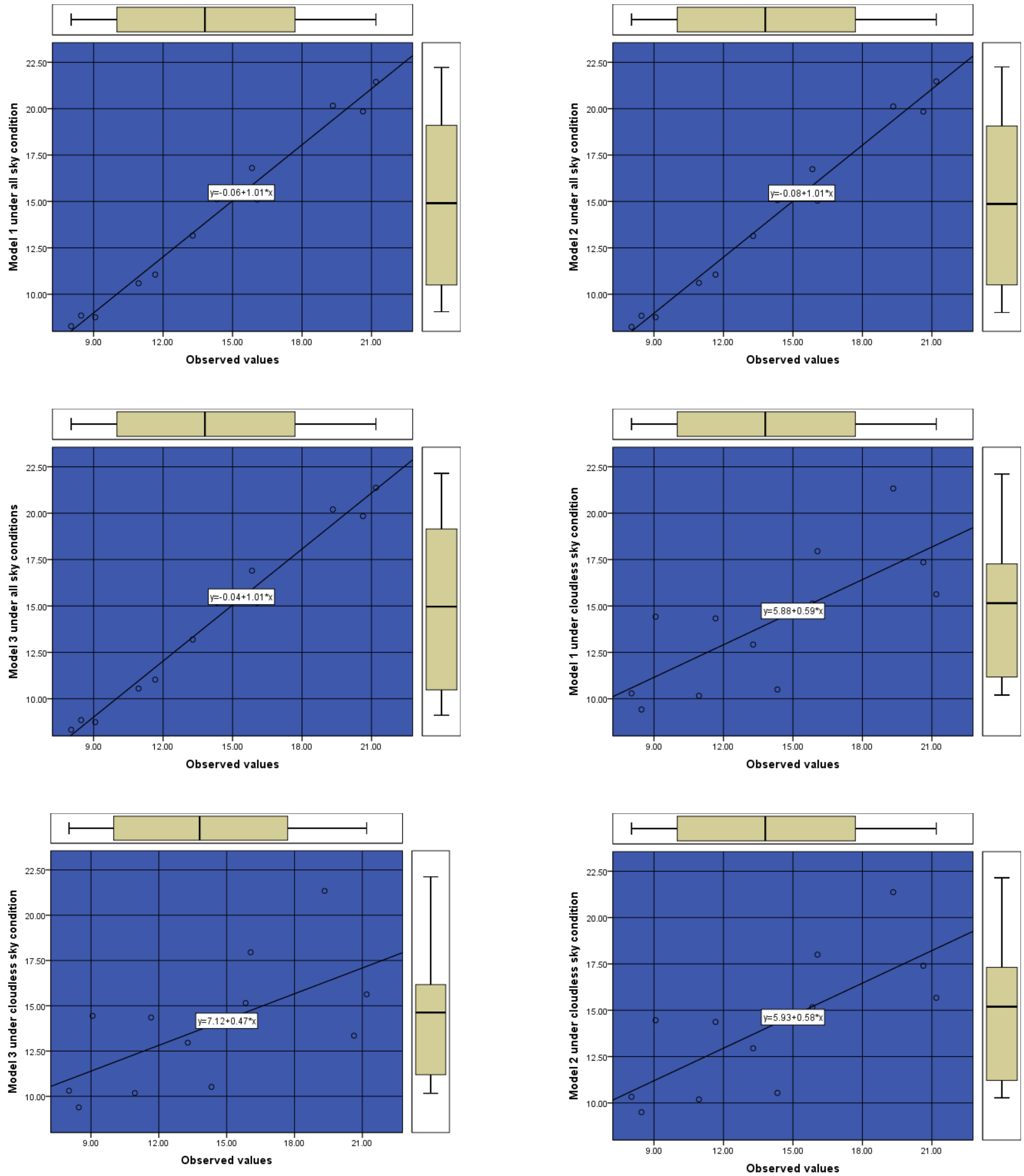

Fig. 7: Scatter Plots and Box diagrams between observed and predicted (models) direct normal irradiance under all sky condition (model 1, 2, 3) and under cloudless sky condition (model 1, 2, 3) for Owerri

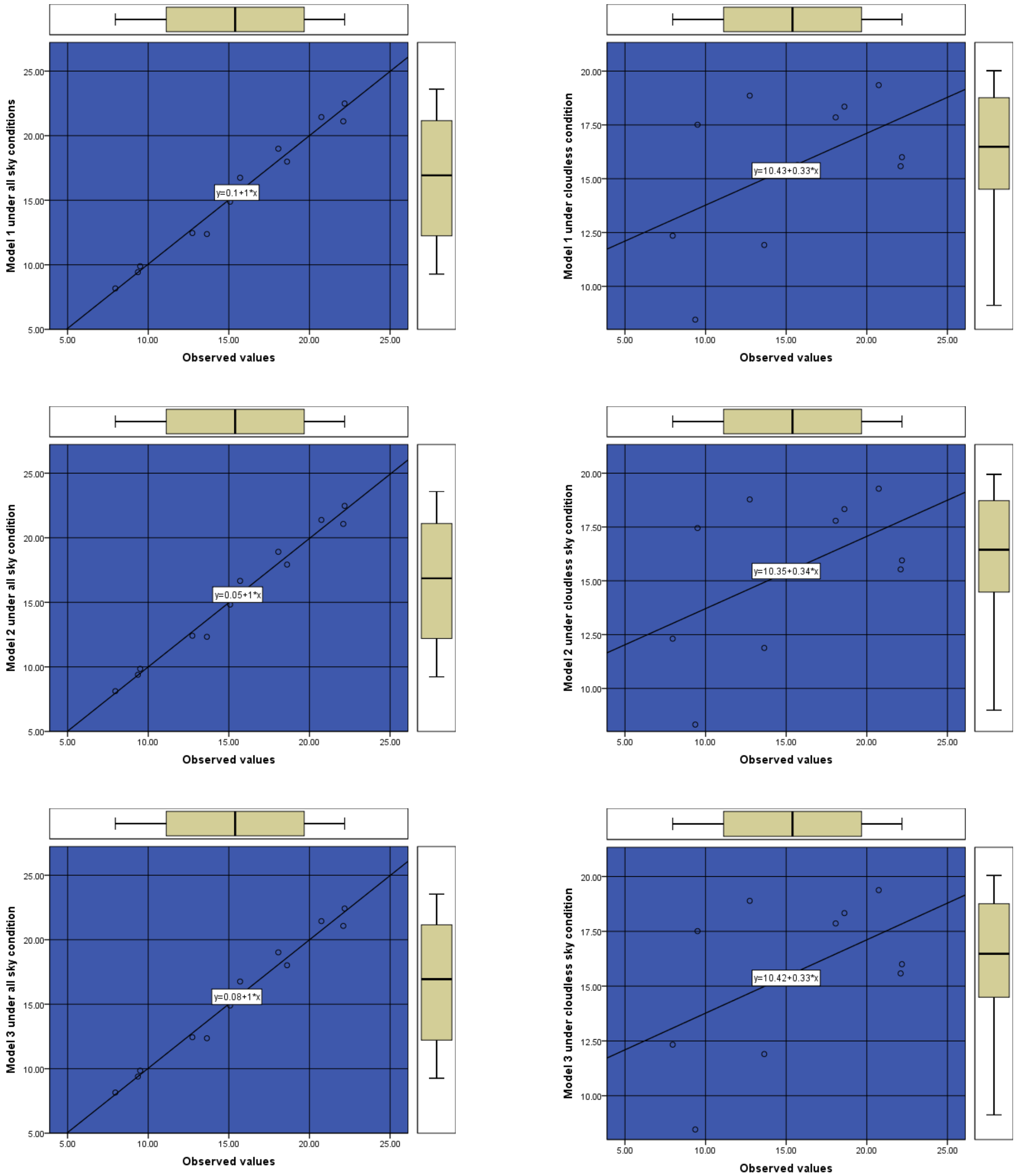

Fig. 8: Scatter Plots and Box diagrams between observed and predicted (models) direct normal irradiance under all sky condition (model 1, 2, 3) and under cloudless sky condition (model 1, 2, 3) for Ibadan

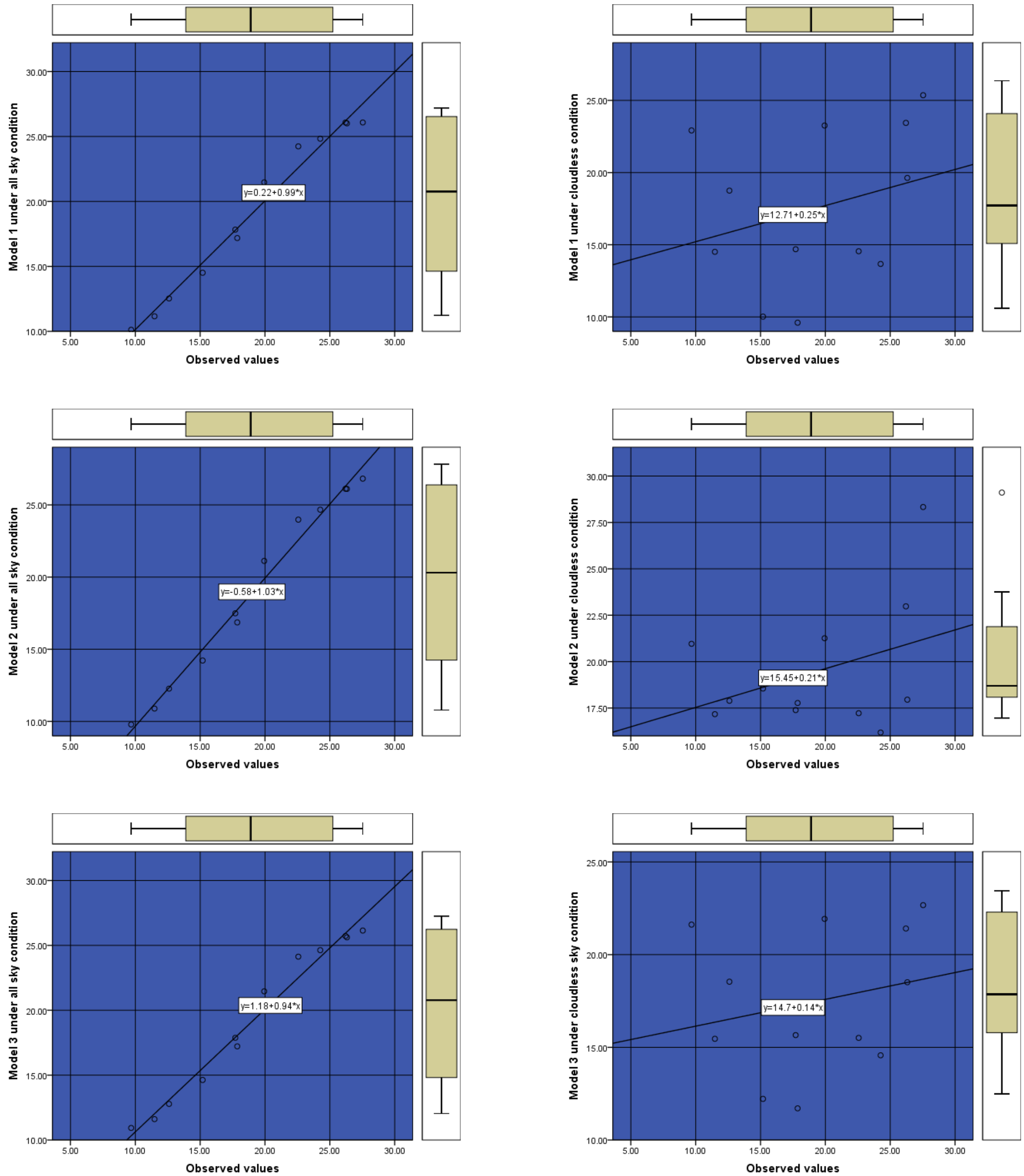

Fig. 9: Scatter Plots and Box diagrams between observed and predicted (models) direct normal irradiance under all sky condition (model 1, 2, 3) and under cloudless sky condition (model 1, 2, 3) for Abuja

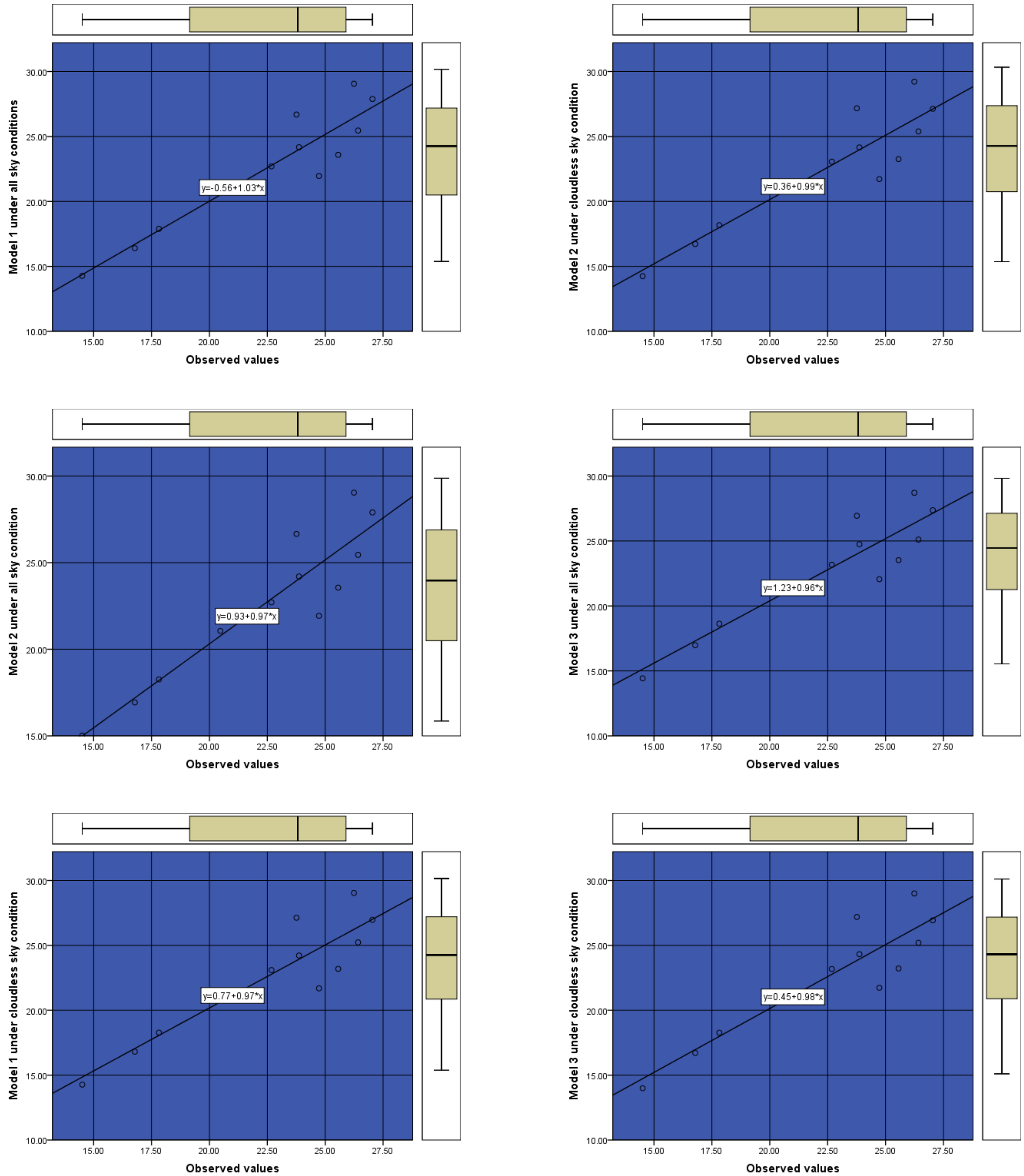

Fig. 10: Scatter Plots and Box diagrams between observed and predicted (models) direct normal irradiance under all sky condition (model 1, 2, 3) and under cloudless sky condition (model 1, 2, 3) for Maiduguri

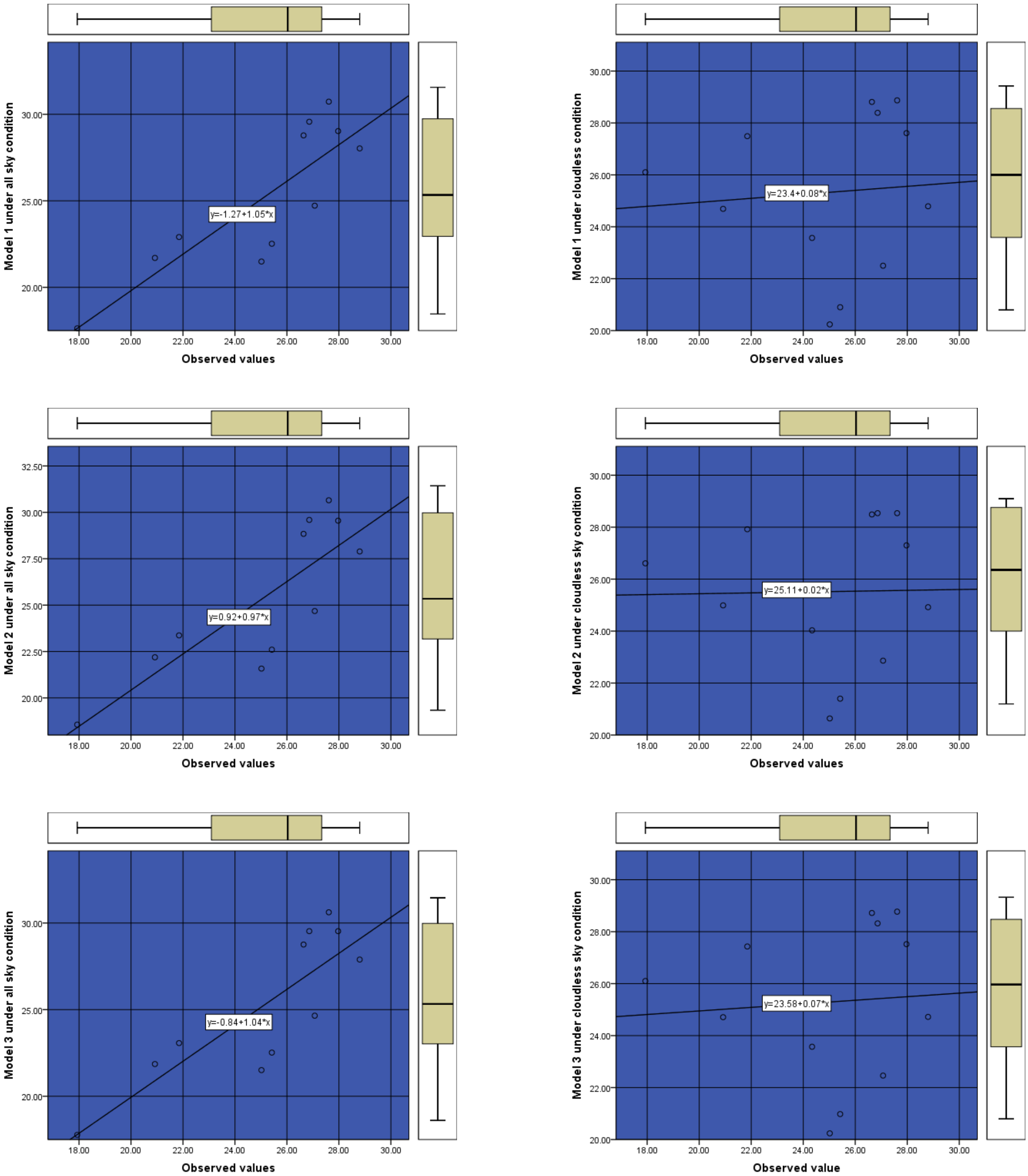

Fig. 11: Scatter Plots and Box diagrams between observed and predicted (models) direct normal irradiance under all sky condition (model 1, 2, 3) and under cloudless sky condition (model 1, 2, 3) for Sokoto.

3.2. Discussions

3.2.1. Variation of atmospheric parameters

The monthly mean daily H_o, H_b and clearness Index (kt) for clear sky and all sky conditions for Port Harcourt, Owerri, Ibadan, Abuja, Maiduguri and Sokoto representing the six tropical ecological zones are presented in Table 2 - 7. The monthly and seasonal variations' change in direct transmittance is associated with sky conditions: large (small) values of kt are related to large (small) values of direct transmittance, as expected from the outputs of decomposition type model and in a tropical site. This trend was observed in Lagos (tropical rain forest) by Maduekwe and Chendo [10, 15]. It was also observed that H_b increases with latitude from Lat 4.4 – 13. 03 ºN along the tropical ecological zones from the far southern tropical ecological zone of mangrove swamp (FSZMS) of Port Harcourt to the far Northern tropical zone of Sahel Savannah (FNZSS) of Sokoto as expected for a tropical site. The same trend was observed by Battles et al. [20] at six stations in Spain. This variation was mainly due to the trends in cloudiness and associated atmospheric moisture with the movement through the Hadley cell circulation system along the equatorial line.

The Nigeria weather condition is classified into two seasons: Dry and wet season. Dry reason is attributed to the influence of inter tropical convergence zone (ITCZ) producing tropical Continental (TC) associated with dry and dusty North – East winds (eateries) which blows from the Sahara Desert and finally prevail over Nigeria; thus producing the dry-season conditions. The implication is that there is a prolonged dry season in the far North, while the far south undergoes short dry periods annually.

With the movement of the ITCZ into the Northern hemisphere, the rain-bearing south westerlies prevail as far inland as possible to bring rainfall during the rainy season. This results to prolonged rainy season in the far South while the far North undergoes short rainy periods annually.

The dry season is from November to March while the wet season starts in April and ends in October. The rainy season is characterized by overcast and heavy rain clouds. This gives rise to the relatively high H_b and low clearness index as observed between the months of May-October compared to the dry-season months for all sky condition. The same trend was observed by Maduekwe and Chendo [10, 15] in Lagos, Nigeria while the clearness index was relatively high under clear sky weather shown in Fig. 5.

The lowest H_b of 6. 30 $MJm^{-2}day^{-1}$ occurred during the months of September for Port Harcourt. This report is comparable with the result registered by Maduekwe and Chendo [10, 15] in Lagos, Sothern Nigeria. While the minimum clearness index of 0.333 was recorded during the months of July and September for Port Harcourt under all sky conditions compared to higher value of 0.52 recorded in the month of February for Owerri in the same tropical zone under clear sky conditions as expected for tropical site. This value is in agreement with the report in Southern Nigeria [23-30]. This is due to the presence of relatively higher cloud cover, relative humidity, prolonged rainy season and more absorption of diffuse solar radiation and near infrared radiation (NIR) in the solar spectrum thereby producing low magnitude of H_b received in the zone.

The maximum values of H_b of 28. 80 $MJm^{-2}day^{-1}$ was recorded in February for Sokoto. While the highest clearness index for all sky conditions is 0.69 recorded during February for Sokoto. However, Sokoto registered the highest value of 0.64 clearness index in the months of March, April and June under clear sky conditions. This could be attributed to the presence of low smog, relative humidity, cloud cover, low absorption of diffuse solar radiation and NIR and prolonged dry season with associated highest latitude (13.067^{0}N) over Sokoto and its environs thereby enhancing H_b and clearness index received at the site. This trend was comparable to the observation of Sambo [31] for clearness index in Northern Nigeria.

3.2.2. Classification of clearness index under all sky conditions

The monthly mean clearness index designates the percentage depletion by the sky of the incoming H and therefore indicates, both the level of availability of solar radiation and changes in the atmospheric condition in a given locality [32-33]. The prevailing clearness index varied between the range of 0.33 – 0.50 and 0.43 – 0.68 between the months of April to October in the rainy season and 0.44 - 0.60 and 0.61 – 0.69 between the months of November to March in the dry Season with an annual range of 0.42 – 0.64 from the FSZMS of Port Harcourt to the FNZSS of Sokoto. These results fall within the report of several researchers in Nigeria literature [23-31].

Using the weather classification proposed by Iqbal [7] which are: (1) heavily overcast weather ($kt \leq 0.4$); (2) partly overcast weather ($0.6 \leq kt \leq 0.4$); and (3) clear weather ($kt \geq 7$). The prevailing weather conditions of the southern ecological zones located at latitude 4.75 and 6. 583 ºN along the mangrove and tropical rainforest of Port Harcourt, Owerri and Ibadan are partly overcast weather except between the months of June to October for Port Harcourt; July to September for Owerri; and August for Ibadan when it falls within the heavily overcast weather as shown in Figure 3. These indicate that the remarkable feature of the southern tropical zones is dominance of heavily overcast weather. It was observed that H_b component of the H increases temporarily with an increase in the clearness index at all sky condition and then increases rapidly as the heavily overcast weather become clearer. This reveals that H_b is optimally controlled by clearness index under all sky conditions in the Southern Nigeria. These results agreed favorably with the report in Southern Nigeria [23-31].

The weather conditions of the Northern tropical zones located between the latitude 9.067 and 13. 067 ºN along the Guinea savannah to Sahel savannah zones of Abuja, Maiduguri and Sokoto are partly overcast weather throughout the year. This also could be due to the presence of low relative humidity, smog, cloud cover, low absorption of NIR, diffuse solar radiation and prevailing prolonged dry season in the zones. Thus, a remarkable feature of the Northern tropical zones is the dominance of partly overcast weather under all sky conditions. The level of availability of clearness index for all sky condition in this research compared favourably to the report of Sambo [31] in Northern Nigeria.

3.2.3. Fitting under various sky conditions

The following observations were deduced from the analyses of the result presented in Table 2 - 7. This is similar to the result recorded by Maduekwe and Chendo [10] for all sky condition and Gueymard [5-6] under clear sky conditions. From Table 2-7, it can be observed that the total annual H_b for Port Harcourt, Owerri, Ibadan and Abuja, Maiduguri and Sokoto are 135.68 $MJm^{-2}day^{-1}$, 169.17 $MJm^{-2}day^{-1}$, 185.96 $MJm^{-2}day^{-1}$, 232.56 $MJm^{-2}day^{-1}$, 269.86 $MJm^{-2}day^{-1}$and 300. 42 $MJm^{-2}day^{-1}$ respectively. The radiation obtained throughout the year is high for all the six tropical ecological zones. This indicates that concentrating solar thermal installations and installations that track the position of the sun such as Concentrating Solar Power (CSP) systems, parabolic tough, linear-freshed or solar tower, high-intensity solar cells and high-temperature heat engines, renewable power plants, heating, natural lighting and production of solar-energy systems have the high potential for H_b utilization at any time of the months as the fluxes are generally greater than 10 $MJm^{-2}day^{-1}$ except in the months of June to October for Port Harcourt, July to September for Owerri and Ibadan respectively in the Southern ecological zones. Hence, solar systems can utilize H_b at any time of the year provided other conditions are favourable except probably in the above mentioned months in the Southern ecological zones.

The coefficients fitted with monthly averages for the six sites, using the quadratic and the proposed linear logarithmic and quadratic exponential proposed models are shown in Table 8. The coefficients of the three (3) models in all the sites, fitted with monthly data are significant up to 5% for clear sky and all sky conditions. They change from place to place with the largest differences being observed for Sokoto under all sky conditions and for all sites under clear sky condition for the three models. This changes depend on the local climatic conditions for all sky conditions while variation for clear sky condition depends on the local climate conditions with low values of H_b under all sky condition correlated with high values of clearness index under clear sky conditions. The coefficient of bo changed in the internal $-1.949 < b_0 < 0.614$, -

2.406 < b_0< -1.295, -4.810 < b_0<-1.414; b_1 in the internal -2.652 < b_1< 5.897, -1.024 < b_1<3.240, -1.503<b_1<5.592; b_2 in the internal -2.692 < b_2< 4.464, -2.000 < b_2<2.702, -4.021 < b_2< 5.690 for all sky conditions. These coefficients are different from 0.208 <b< 2.16 obtained by Maduekwe and Chendo [10, 15] at Lagos, Nigeria using a short term data from two years (1990 – 1991) obtained from global and diffuse solar irradiance incident on a horizontal surface within (Lat 6.58°N, Long 3.33°E) employing monthly mean daily values with quadratic model of direct transmittance and clearness index relations. This variation could be attributed to the short-term data (1990 – 1991) used as short data increase error in estimation and local climatic changes from 1990 – 1991 compared to 1983 – 2005 employed in this study.

Similar weather variation and climate local conditions range of 0.941 – 0.990 were observed for Port Harcourt, Owerri, Ibadan and Abuja along mangrove swamp of Port Harcourt to Guinea Savannah of Abuja as shown in Table 8. This reveals that direct transmittance is optimally controlled by clearness index from FSZMS of Port Harcourt to North-Central Zone of Guinea Savannah (NCZGS) of Abuja in spite of the low correlation obtained under clear sky conditions. That is, 94.1 – 99.0% of the clearness index can be accounted using direct transmittance while 1 – 5.9% are accounted by other independent atmospheric and meteorological variables that influence direct transmittance such as relative humidity, cloud cover, precipitation because of the presence of prolonged rainfall, heavy smog, short period of dry season, high absorption of H_b and NIR in the solar spectrum to mention but few that are highly prevalent in these zones with their associated independent atmospheric variables not fitted in the three models under all sky conditions. This range is similar to 0.991 recorded by Maduekwe and Chendo [10, 15] in Lagos, South-West Zone of Tropical Rainforest (SWZTR), Nigeria.

Comparable local climate conditions range of 0.719 – 0.896 were registered for Sokoto and Maiduguri along North-East Zone of Sudan Savannah (NEZSS) of Maiduguri to North-West Zone of Sahel Savannah (NWZSS) of Sokoto with the corresponding lower values obtained in clear sky conditions. This indicates that direct transmittance is not optimally controlled by clearness index under all sky or clear sky conditions using data employed in this study. That is, 71.9 – 89.6% of the clearness index can be accounted for direct transmittance while 10.4 – 28.1% are accounted by other independent atmospheric and meteorological variables that influence direct transmittance such as temperature, sunshine duration, ITCZ producing TC associated with dry and dusty North-East winds that are highly prevalent in these zones. This range is lower than the 0.991 recorded by Maduekwe and Chendo [10-15] in SWZTR of Lagos primarily because the local climate conditions.

The maximum correlation of 0.990 was recorded in NCZGS of Abuja using model 2. This could be attributed to the position of Abuja in Nigeria. The controlling local climate conditions in the Southern tropical zones of Port Harcourt, Owerri, and Ibadan and that of two Northern tropical zones of Maiduguri and Sokoto contribute little influence in the NCZG of Abuja. That is, trends in cloudiness and associated atmospheric moisture with the movement of the Hadley cell circulation system along the equatorial line finds a way of balancing the cloudiness in the NCZGS of Abuja. The minimum correlation obtained was 0. 719 recorded in the FNZSS of Sokoto using model 1 and 2 as a result of the local climate conditions in the zone.

However, the correlations were generally weaker under clear sky conditions with the range of 0.381 – 0.604 in the Southern ecological zones compared Northern ecological zones that revealed appreciable correlation of 0.311 – 0.885 except Sokoto in the FNZSS that recorded the weakest correlation between the observed and predicted value of 0.061 – 0.143. This variance could be attributed to the estimation of direct transmittance under all sky condition with clearness index under clear sky.

The comparison between the observed and predicted H_b using the three (3) models under all sky and clear sky conditions are shown in Fig. 6-11 for the six tropical zones. The results indicate a good agreement between the observed and predicted H_b.

3.2.4. Statistical performance of the models

The performances of the models are evaluated and compared using statistical parameter such as MBE and RMSE. The summary of the error parameters is presented in Table 9. MBE is a measure of evaluating over estimation and underestimation of the models in the six sites. Positive values of MBE indicate overestimation in predicted values of the H_b, while negative values indicate underestimation. From Table 9, it is clear that in the Southern zones, the monthly mean daily H_b for Port Harcourt and Owerri slightly overestimated all the models except model 2 for clear sky conditions. Ibadan overestimated using all the models under all sky condition and underestimated under clear sky conditions. In the Northern zones, all the models underestimated for Maiduguri and Sokoto under all sky conditions and clear sky conditions. While Abuja was underestimated under all sky conditions using models 1 and 3 and all the models overestimated under clear sky condition except model 2. This confirms that the proposed models accurately fitted the local climate conditions in three tropical ecological zones of mangrove swamp, Tropical Rain Forest and Guinea Savannah located in Port Harcourt (South-south region), Owerri (South-East), Ibadan (South -West) and Abuja (North-Central). While Maiduguri and Sokoto local climate conditions require more/other atmospheric/metrological parameters to accurately fit in the proposed models. The RMSE test provides information on the short-term performance of the studied model as it allows a term by term comparison of the actual derivation between the predicted and observed values. Table 9 shows that the RMSE for the Southern tropical zones ranged from 0.15 – 0.28 under all sky conditions and 0.72 – 0.87 under clear sky conditions while the Northern tropical zones ranged from 0.02 – 0.52 under all sky conditions and 0.36 – 1.74 under all sky conditions. The variation could be attributed to the local climate condition influencing each zone as a result of the trends in cloudiness and associated atmospheric moisture with the movement through the Hadley cell calculation system along the obtained equatorial line. These results fall within 0.04 estimation error observed by Maduekwe and Chendo [10-15] in Lagos. These imply that the regression lines fit the predicted data in the Southern zones while higher values obtained in the Northern zones indicate that the proposed models needed other meteorological parameters to accurately fit the local climate conditions.

4. Conclusion

The analysis of the influence of clearness index on H_b based on the radiation data recorded for Port Harcourt, Owerri, Ibadan, Abuja, Maiduguri and Sokoto representing the six tropical ecological zones in Nigeria was carried out. The annual clearness index implies that the prevailing weather condition in the Southern tropical zones indicates that Port Harcourt, Owerri and Ibadan are heavily overcast while Abuja, Maiduguri and Sokoto experienced partly overcast weather. Higher values of H_b were observed in the FNZSS of Sokoto while lower values were recorded in the FSZMS of Port Harcourt indicating an increasing trend of H_b from FSZMS to FNZSS, principally caused by the trends in cloudiness and associated atmospheric moisture with the movement of the Hadley cell calculation system along the equatorial line from the FSZMS to FNZSS. Generally, the proposed model suitably predicted stations in the southern tropical zones (Port Harcourt Owerri and Ibadan) and Abuja (NCZGS) and underestimated stations in the North East zone of Sudan Savannah (NEZSS) of Maiduguri and FNZSS of Sokoto. For reasonably reliable estimation, we therefore recommend that the proposed model will function efficiently for any station in mangrove swamp, tropical rainforest and guinea savannah tropical zones in Nigeria. This research paper is the first attempt to qualify H_b component in the six tropical ecological zones in Nigeria; thus our models can be used to estimate

H_b parameters for locations with similar climatological conditions where H data are readily available.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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