A Semi-Empirical Model for Vertical Extrapolation of Surface Refractivity over Nigeria

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A semi-empirical model was developed from a vertical refractivity profile at Akure latitude $7^0$15'' N, longitude $5^0$12'' E and 286m above sea level in the south-western part of Nigeria. The refractivity profile was obtained by positioning automatic weather stations on a 250m tall mast at the surface, 50m, 100m, 150m, and 200m. The refractivity at each of these heights was calculated over a period of four years (2007-2010) and the averaged refractivity over the study period at each height was used to produce the refractivity profile. A semi-empirical model was obtained from the profile and it was used to predict refractivity at 100m for other location over Nigeria. The predicted values of refractivity obtained from the model have standard deviations ranging from -9.72 to ±11.77 when compared with the values calculated from the measured meteorological data at the same height at Akure, Nsukka, Minna and Sokoto.

1. Introduction

The propagation of EM waves is affected by many processes in the lower atmosphere. One of these is refractive effect, which relates to processes associated with the bending of EM waves and are related to the vertical pressure, temperature and humidity distributions in the atmosphere. These effects are sometimes dramatic and can be the dominant propagation processes within, near and beyond the horizon.

Profiles of refractivity gradients within 1 km of the atmosphere are important for the estimation of some propagation parameters, such as super-refraction and ducting phenomena, and their effects on radar observations and VHF field strength at points beyond the horizon [1].

Multipath effects also arise due to large scale variations in atmospheric radio refractive index, such as horizontal layers with very different refractivity [2]. This effect becomes noticeable, when the same signal takes different paths to its target and the rays arriving at different times thereby interfering with each other during propagation through the troposphere. The consequence of this large scale variation in the atmospheric refractive index is that radio waves propagating through the atmosphere becomes progressively curved towards the earth. Thus, the range of the radio waves is determined by the height dependence of the refractivity. Therefore, the refractivity of the atmosphere will not only affect the curvature of the ray path but will also provide some insight into the fading of radio waves through the troposphere.

The determination of refractivity gradient, which is very important as described above, depends on the availability of upper air data. The upper air data is very difficult to get in Nigeria because the few radiosonde stations that were available are no longer functional. Recently, efforts have been made by different researchers to place weather stations on a tall mast to collect meteorological data for the lower atmosphere in order to be able to determine refractivity gradient of the lower atmosphere.

This effort is however hampered due to the non availability or the difficulty encountered in securing suitable mast. To solve this problem, there is a need to develop a model that can extrapolate the surface refractivity to a desired height wherever the surface data is available.

Two refractivity parameters are often encountered in estimating radio propagation effects; these are surface refractivity N_s and surface refractivity reduced to sea level N_o. It is however often advisable to use N_s because it is readily available.

For long-term median estimates, an empirical relation can be established between the average mean refractivity gradient $\Delta N/\Delta h$ for the first kilometre above the surface and the value of the average monthly mean refractivity Ns at the surface. This has been established for various locations around the world as given by [3, 4]. For

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the continental United States the relationship is

$$\frac{\Delta N}{\Delta h} = -7.32\exp\,(0.005577 N_s)$$

where ΔN/Δh is in *N*-units/km and N_s is in *N*-units. For Germany and the United Kingdom, respectively, it is

$$\frac{\Delta N}{\Delta h} = -9.30\exp\,(0.004565 N_s)$$

and

$$\frac{\Delta N}{\Delta h} = -3.95\exp\,(0.0072 N_s)$$

These relationships are valid for $250 \le Ns \ge 400$ *N*-units and are only applicable to average negative gradients close to the surface.. The value of *Ns* is a function of temperature, pressure and humidity, and therefore decreases on the average with elevation.

This study intends to develop such an exponential semi-empirical model for the determination of upper air refractivity over Nigeria, where the surface refractivity data is available.

2. Theory

Radio-wave propagation is determined by changes in the refractive index of air in the troposphere. Because it is very close to unity (about 1.0003), the refractive index of air is measured by a quantity called the radio-refractivity *N*, which is related to refractive index, *n* as [5]

$$N = (n-1) \times 10^6 \qquad (1)$$

In terms of the measured meteorological quantities, the refractivity *N*, can be expressed as

$$N = 77.6\frac{P}{T} + 3.73\ X\ 10^5 \frac{e}{T^2} \qquad (2)$$

where *P* is atmospheric pressure (hPa), *e* is water vapour pressure (hPa) and *T* is absolute temperature (K).

Eqn.2 may be used for radio frequencies up to 100 GHz [1]. The error associated with the use of this expression is less than 0.5% [5].

The water vapour pressure *e* is usually calculated from the relative humidity and saturated water vapour using the expression

$$e = \frac{He_S}{100} \qquad (3)$$

where

$$e_s = aexp\left\{\frac{bt}{t+c}\right\} \qquad (4)$$

H is relative humidity (%), *t* is temperature in degree Celsius (◦C) and e_S is saturation vapour pressure (hPa) at the temperature *t* (◦C),b = 17.502, a = 6.1121 and c = 240.97 [6].

The vertical gradient of refractivity in the lower layer of the atmosphere is an important parameter in estimating path clearance and propagation effects such as sub-refraction, super-refraction, or ducting.

In order to draw comparisons between different regions, it is essential to adopt a reference level, which means that the effects induced by altitude have to be eliminated. The basic profile proposed hereafter has been adopted by the ITU-R. As altitude rises, the refractive index *n* generally decreases and tends towards the unit, while the refractivity *N* tends towards zero.

However, this decay law is considerably disturbed in the troposphere by two factors:

(i) the dependence of the average decrease of *n* on the decrease of the atmospheric pressure;
(ii) the variations around the average caused by irregularities in the temperature and relative humidity.

Since the decrease of the atmospheric pressure follows an exponential law, the decay law of the refractive index is also exponential. This led to the introduction of a reference atmosphere for refraction, defined by the following equation [7]

$$N(h) = N_o exp^{-(\frac{h}{H})}$$

where N_o is the average value of refractivity extrapolated to the level of the sea (315 N-units), *h* is the height above the sea level and h_o is the reference height (h_o = 7.35 km in general).

3. Methodology

For four years, meteorological data (Jan. 2007 - Dec. 2010) was collected from Akure using weather stations installed on a 200m high mast at the surface, 50m, 100m, 150m and 200m. Hourly average of the data set was taken to produce 24 data point representing the diurnal variation at each height for each month of the years under study. The 24 data point for each month at each height was then averaged to produce the monthly average of the data for each level. The monthly averaged data for each year was then averaged to produce an annual average for each year. The annual average was then averaged to produce a single data point representing the average data over four years for each level at which the data was collected. The average data over four years at each of the level was plotted against height to obtain the vertical profile of refractivity. A semi-empirical formula for the vertical refractivity variation was obtained from the profile. The model was then used to calculate refractivity at the height of 100m at Akure, Nsukka, Minna and Sokoto. The predicted data by the model was compared with refractivity calculated at this height for all the locations from measured meteorological data at the height of 100m. Fig. 1 shows the map of Nigeria with the study areas. The result was presented in terms of percentage error and deviation of the predicted value by the model from the measured value as calculated from the measured meteorological parameters.

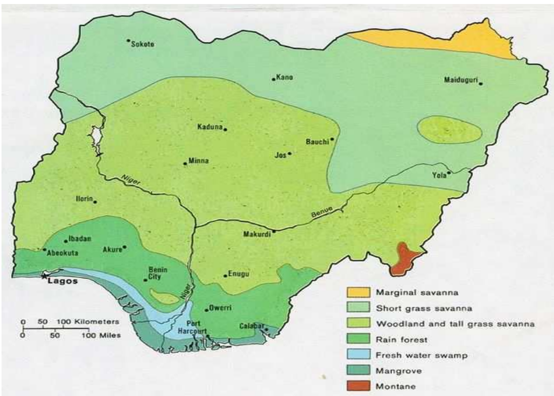

Fig.1: Map of Nigeria.

4. Discussion

Average annual refractivity value at the surface, 50m, 100m, 150m, and 200m for 2007, 2008, 2009, and 2010 was obtained from meteorological data collected at these heights. The average annual refractivity value at each height was then averaged over the four years under consideration and was plotted against height as shown in Fig. 2. The plot showed a general decrease in refractivity with height. This obvious decrease in refractivity with height was attributed to the fact that the meteorological parameters used in the calculation have all been established to decrease with height [8, 9]. Considering the fact that the meteorological parameters of temperature, pressure and relative humidity have an exponential vertical variation [7], it follows that an exponential semi-empirical relationship between the refractivity and height can be obtained and it is given as

$$N = N_s \exp(-0.26)h$$

Where N is refractivity (*N-units*) at any height N_s is the refractivity (*N-units*) at the surface and h is the height under consideration in kilometers.

This semi-empirical relationship was tested with the data collected at surface from Akure, Nsukka, Minna and Sokoto to calculate refractivity at the height of 100m and compare it with the refractivity determined from the meteorological data measured at 100m from these locations. Table 1.1a to Table 1.4b present the comparison between the measured value and the predicted value. It also gives the deviation and percentage error for each location with negative value of error showing that the predicted value is higher than the measured value. Whenever the measured value is greater than the predicted value, it is likely an indication of temperature inversion, which cannot be predicted by the semi-empirical model.

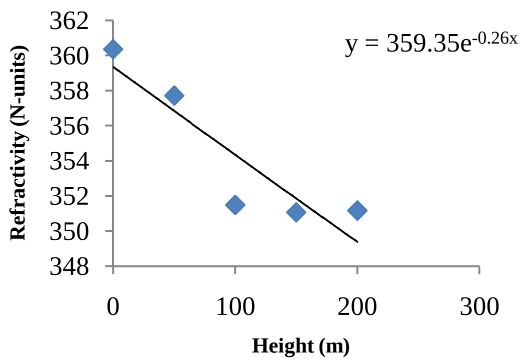

Fig.2: Variation of Refractivity with Height at Akure.

Table 1.1a: Comparison of measured and predicted refractivity over Akure for dry season.

Time	Measured Values	Predicted Values	Deviation	Percentage error
1	349.2508271	348.9841311	0.266696007	0.076362312
2	349.6332826	350.528565	-0.895282434	-0.256063275
3	350.7684881	351.7211531	-0.952665042	-0.271593679
4	351.0772251	351.8467438	-0.769518748	-0.219187886
5	350.2944867	351.9055426	-1.611055874	-0.45991471
6	349.9183726	351.9804652	-2.062092647	-0.589306766
7	348.6250985	351.5119992	-2.886900786	-0.828081741
8	348.3964463	352.6514605	-4.255014164	-1.221313882
9	346.7813461	354.0010574	-7.21971132	-2.081920323
10	345.2470711	351.4348053	-6.187734176	-1.792262613
11	342.8119972	345.8209254	-3.008928155	-0.877719619
12	336.1198484	339.6993178	-3.579469411	-1.064938422
13	333.4304446	337.5926619	-4.162217312	-1.248301521
14	331.4695382	334.1623172	-2.692779049	-0.812376022
15	328.9796485	332.0501839	-3.070535424	-0.933351178
16	332.1953685	330.0643625	2.131005977	0.641491778
17	334.2948657	330.8662914	3.428574312	1.025613811
18	337.2926101	333.5051345	3.787475539	1.122904987
19	341.6148449	338.7409115	2.87393334	0.841278821
20	346.5727682	343.1761028	3.396665392	0.980072788
21	347.9085997	346.4392756	1.469324115	0.422330496
22	347.4666149	348.5801177	-1.113502808	-0.32046325
23	351.0924264	351.0674315	0.024994961	0.007119197
24	339.2060756	354.2248557	-15.01878011	-4.427627096

Table 1.1b: Comparison of measured and predicted refractivity over Akure for rainy season.

Time	Measured Values	Predicted Values	Deviation	Percentage error
1	366.5941048	361.0708941	5.52321068	1.506628342
2	366.9904642	360.298436	6.69202816	1.823488297
3	368.5181031	359.4217551	9.09634797	2.468358513
4	367.6104286	359.0741683	8.5362603	2.322094161
5	367.5558073	359.0278828	8.52792452	2.320171346
6	367.8209269	359.2179342	8.60299274	2.338907907
7	368.1484798	360.3057067	7.84277307	2.130328795
8	369.0597931	362.5632247	6.49656839	1.760302398
9	370.065626	364.5403223	5.52530376	1.493060521
10	372.1088673	364.9722644	7.13660288	1.91788036
11	367.6427555	362.8347795	4.80797601	1.307784783
12	365.3614513	361.8211523	3.54029901	0.968985369
13	366.8084134	360.0037727	6.8046407	1.855093953
14	364.336476	358.4061503	5.93032565	1.627705718
15	365.6748982	357.7329137	7.94198445	2.171870285
16	363.1774034	357.2917562	5.88564725	1.620598417
17	358.680068	357.8838297	0.79623833	0.221991239
18	360.6782056	358.7867377	1.89146781	0.524419768
19	361.2226733	359.9188227	1.30385066	0.360954822
20	365.4419739	360.1695862	5.27238774	1.442742792
21	365.5171002	361.0169277	4.50017246	1.231179734
22	367.5542825	361.0634609	6.4908216	1.765949116
23	368.0359154	361.3115465	6.7243689	1.82709584
24	366.9768014	361.3126194	5.66418192	1.543471386

Table 1.2a: Comparison of measured and predicted refractivity over Nsukka for dry season.

Time	Measured Values	Predicted Values	Deviation	Percentage error
1	366.5941048	361.0708941	5.52321068	1.506628342
2	366.9904642	360.298436	6.69202816	1.823488297
3	368.5181031	359.4217551	9.09634797	2.468358513
4	367.6104286	359.0741683	8.5362603	2.322094161
5	367.5558073	359.0278828	8.52792452	2.320171346
6	367.8209269	359.2179342	8.60299274	2.338907907
7	368.1484798	360.3057067	7.84277307	2.130328795
8	369.0597931	362.5632247	6.49656839	1.760302398
9	370.065626	364.5403223	5.52530376	1.493060521
10	372.1088673	364.9722644	7.13660288	1.91788036
11	367.6427555	362.8347795	4.80797601	1.307784783
12	365.3614513	361.8211523	3.54029901	0.968985369
13	366.8084134	360.0037727	6.8046407	1.855093953
14	364.336476	358.4061503	5.93032565	1.627705718
15	365.6748982	357.7329137	7.94198445	2.171870285
16	363.1774034	357.2917562	5.88564725	1.620598417
17	358.680068	357.8838297	0.79623833	0.221991239
18	360.6782056	358.7867377	1.89146781	0.524419768
19	361.2226733	359.9188227	1.30385066	0.360954822
20	365.4419739	360.1695862	5.27238774	1.442742792
21	365.5171002	361.0169277	4.50017246	1.231179734
22	367.5542825	361.0634609	6.4908216	1.765949116
23	368.0359154	361.3115465	6.7243689	1.82709584
24	366.9768014	361.3126194	5.66418192	1.543471386

Table 1.2b: Comparison of measured and predicted refractivity over Nsukka for rainy season.

Time	Measured Values	Predicted Values	Deviation	Percentage error
1	336.6501374	337.4923486	-0.84221115	-0.25017401
2	335.9416789	333.8481849	2.09349393	0.623171836
3	334.5442917	329.8102354	4.73405623	1.415076074
4	334.0486277	329.3709981	4.67762955	1.40028402
5	335.3173096	328.8841303	6.43317922	1.918534783
6	337.1718179	330.3732274	6.79859056	2.016357891
7	337.7171065	333.1063196	4.61078686	1.365280813
8	339.2853042	335.788605	3.49669913	1.030607305
9	339.93909	338.7629792	1.17611086	0.345976941
10	340.5239526	340.2429151	0.28103749	0.082530901
11	340.8330208	340.6122425	0.22077833	0.064776097
12	338.8788474	340.4933249	-1.61447752	-0.47641732
13	338.3913576	339.3010996	-0.90974201	-0.268843159
14	338.6652624	340.2969086	-1.63164622	-0.4817873
15	340.0198265	344.3457834	-4.32595692	-1.272266081
16	340.9226287	345.6136718	-4.69104307	-1.375984659
17	340.6332752	346.3183362	-5.68506109	-1.668968213
18	340.1673897	347.7814631	-7.61407342	-2.238331377
19	340.855792	349.0669305	-8.21113849	-2.408977253
20	343.017056	349.7145835	-6.69752752	-1.952534838
21	343.4999903	351.0346785	-7.53468827	-2.193504654
22	344.503458	350.3674668	-5.86400873	-1.702162517
23	345.101785	348.3532469	-3.25146194	-0.942174769
24	345.4594101	344.5315924	0.92781773	0.268575033

Table 1.3a: Comparison of measured and predicted refractivity over Sokoto for rainy season.

Time	Measured Values	Predicted Values	Deviation	Percentage error
1	362.0428217	360.8782176	1.16460411	0.321675792
2	362.2502228	361.3128296	0.93739323	0.25876954
3	362.3910533	360.6152544	1.77579896	0.490022848
4	362.1987381	360.0433866	2.15535153	0.59507428
5	362.0970673	360.499473	1.59759426	0.441206076
6	362.1908106	361.6084571	0.58235354	0.160786393
7	362.4887713	362.6439499	-0.1551785	-0.042809201
8	362.9608375	363.207085	-0.2462475	-0.067844101
9	363.8553713	362.921458	0.93391335	0.256671585
10	364.73952	363.1217592	1.61776077	0.443538659
11	364.6364739	362.552604	2.08386984	0.571492429
12	363.7927161	361.0795758	2.71314035	0.745792929
13	361.5397805	358.7853072	2.75447325	0.761872801
14	359.5646685	357.7243272	1.84034137	0.511824861
15	358.3663227	357.5105765	0.85574616	0.238790897
16	358.6387972	357.7193312	0.91946599	0.256376609
17	360.6691686	356.9817722	3.68739643	1.02237639
18	361.1918445	356.4881524	4.70369207	1.302269733
19	362.5908	357.2718153	5.3189847	1.466938681
20	362.0196082	358.180171	3.83943719	1.060560562
21	363.3830982	358.5118552	4.87124296	1.340525464
22	363.1702578	359.3571909	3.81306694	1.049939212
23	362.5237768	359.9117328	2.61204399	0.7205166
24	363.4716896	360.5789576	2.89273202	0.795861713

Table 1.3b: Comparison of measured and predicted refractivity over Sokoto for dry season.

2	277.5385852	267.8726181	9.66596715	3.482747143
3	279.5697172	268.0430271	11.5266902	4.123010985
4	281.5273152	269.7540037	11.7733115	4.181942892
5	283.5886827	270.450573	13.1381097	4.632804672
6	284.7538204	271.7697121	12.9841083	4.559766153
7	285.7563451	273.9772426	11.7791025	4.122079088
8	287.538858	275.8904686	11.6483893	4.051066146
9	289.3200773	277.3690782	11.950999	4.130718874
10	290.7308778	277.5274986	13.2033792	4.541443735
11	290.4079461	277.8003714	12.6075747	4.341332563
12	288.5786478	276.5773467	12.0013011	4.158762665
13	285.7746267	273.5774482	12.1971785	4.268111061
14	283.0073046	270.5904631	12.4168414	4.387463238
15	280.276652	268.8028917	11.4737603	4.093726754
16	278.4668701	266.6661962	11.8006739	4.237729928
17	277.6048829	266.2462402	11.3586427	4.091658108
18	277.0806275	265.3550469	11.7255806	4.231829803
19	277.222823	265.1073321	12.1154908	4.370307868
20	277.0020659	265.6510304	11.3510355	4.097816188
21	278.011256	265.9722344	12.0390216	4.330407961
22	278.4748006	266.8497328	11.6250678	4.17454928
23	278.8416953	267.2446643	11.597031	4.159001762
24	278.2050053	267.2230411	10.9819642	3.947435876

Table 1.4a: Comparison of measured and predicted refractivity over Minna for rainy season.

Time	Measured Values	Predicted Values	Deviation	Percentage error
1	336.4046183	344.4590422	-8.05442	-2.394266724
2	336.5575236	345.1244485	-8.56692	-2.545456366
3	337.4422234	345.8206894	-8.37847	-2.482933478
4	337.1637484	345.917256	-8.75351	-2.596218481
5	337.4719655	346.9615964	-9.48963	-2.811976059
6	337.7162144	347.1775034	-9.46129	-2.801550118
7	338.2822061	347.5195674	-9.23736	-2.730667193
8	338.34593	347.6647112	-9.31878	-2.754217029
9	338.6265434	348.1364776	-9.50993	-2.808384155
10	339.1975387	349.1388863	-9.94135	-2.930843072
11	339.470689	349.7094599	-10.2388	-3.016098656
12	339.2488367	349.2842207	-10.0354	-2.958118904
13	338.9667009	349.4258985	-10.4592	-3.085612104
14	338.7345113	348.189751	-9.45524	-2.791342292
15	336.9715792	346.5763583	-9.60478	-2.850323201
16	335.8254485	345.6294477	-9.804	-2.919373512
17	335.187806	345.0676148	-9.87981	-2.947544218
18	334.0790497	344.5777213	-10.4987	-3.142571102
19	333.608955	344.4616434	-10.8527	-3.253116635
20	333.5611587	345.5543956	-11.9932	-3.595513634
21	334.5037914	344.8450836	-10.3413	-3.091532143
22	334.2290789	343.0851446	-8.85607	-2.649699352
23	334.077057	344.5099888	-10.4329	-3.122911786
24	335.4477495	345.5790104	-10.1313	-3.020220262

Table 1.4b: Comparison of measured and predicted refractivity over Minna for dry season.

Time	Measured Values	Predicted Values	Deviation	Percentage error
1	302.9834078	310.9224593	-7.9390515	-2.620292503
2	303.0258743	307.5337835	-4.5079093	-1.487631799
3	301.8458979	305.3037896	-3.4578917	-1.145581823
4	300.9301429	304.5442318	-3.6140889	-1.200972709
5	300.638483	303.6039072	-2.9654242	-0.986375457
6	300.943347	304.8339508	-3.8906038	-1.292802718
7	301.7532899	308.5569704	-6.8036806	-2.25471628
8	303.1057556	308.4728763	-5.3671207	-1.770708929
9	302.7925855	309.6602294	-6.8676439	-2.268101737
10	303.8054713	311.6768133	-7.871342	-2.590915159
11	304.1278446	309.7806087	-5.6527641	-1.858680218
12	301.0985331	307.0116903	-5.9131572	-1.963861169
13	299.1451803	303.6267746	-4.4815943	-1.498133539
14	297.0085824	301.5063845	-4.4978021	-1.514367729
15	293.9632972	299.2969491	-5.333652	-1.814393839
16	292.9846369	298.4482544	-5.4636174	-1.86481363
17	291.3485619	296.7949232	-5.4463613	-1.869362696
18	291.2688745	298.2314493	-6.9625748	-2.390428717
19	292.7211318	299.6890889	-6.967957	-2.380407919
20	293.2864882	300.3072066	-7.0207184	-2.393809007
21	294.3451331	302.2689485	-7.9238154	-2.692015096
22	298.1170388	305.274817	-7.1577782	-2.400996004
23	300.7308437	307.2055363	-6.4746927	-2.152985898
24	301.4766352	309.4739997	-7.9973645	-2.652731115

The standard deviation at all stations is given in Table 1.5. From Table 1.5, the semi-empirical formula developed here tends to show a deviation of 5.9 in rainy and -1.75 in dry seasons at Akure. At Nsukka, the deviation is 2.22 for rainy seasons and -0.95 for dry seasons. The deviation at Sokoto is 0.75 in rainy seasons and 11.75 for dry seasons. The deviation at Minna is -9.72 for rainy seasons and -5.86 for dry seasons. The deviation in the Southern part of the country (Akure and Nsukka) tends to be more positive in the rainy seasons than in the dry seasons. At Sokoto, which is located at the extreme northern part of the country, the deviation tends to be more positive in the dry seasons. At Minna, which is located midway between these two extremes, the deviation is negative for both seasons though more positive in the dry seasons. This variation pattern agrees with the pattern of change in meteorological condition from the southern part to the northern part of Nigeria. The results also generally show a better agreement with the measured values in the dry seasons, however, with the exception of Sokoto, which shows a better agreement in the rainy seasons.

Table 1.5: The standard deviation of the predicted values of refractivity from the measured values.

Station Name	Standard Deviation	
	Rainy Season	Dry Season
Akure	5.90	-1.75
Nsukka	2.22	-0.96
Sokoto	0.75	11.77
Minna	-9.72	-5.86

5. Conclusion

A semi- empirical relationship developed from vertical refractivity profile over Akure was used to calculate refractivity at the height of 100m for four locations and the result obtained compared adequately with the result from measured data at the same height. The predicted values of refractivity from the model have standard deviation ranging from -9.72 to 11.77 when compared with the values calculated from measured meteorological data at the same height at Akure, Nsukka, Minna and Sokoto.

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