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Wind Energy Density in Nigeria as Estimated From the ERA Interim Reanalysed Data Set

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Authors' contributions

This work was carried out in collaboration between both authors. Author AO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript and managed literature searches. Authors AO and DA managed the analyses of the study and literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Inadequate power generation from hydro and fossil fuel electrical power stations in Nigeria demands seeking additional sources of power generation. This study focuses on wind source with the aim to determine suitable locations for commercial wind farms. Using reanalysed wind speeds data from European Reanalysis project (ERA interim), wind speeds at the turbine height of 70 m have been estimated for 39 stations over Nigeria. Because local surface features of each station have strong effect on wind speeds, profile of wind has been estimated by taking into account the surface albedo, cloud cover and atmospheric stability functions. By using the two - parameter Weibull function, this study has delineated area (stations) characterised by persistent wind flows adequate for commercial electrical power generation. Calculated usable electrical output from General Electric 1.5xle type turbine in the identified potential areas ranges between 2.5 and 11.3 MW in southern station of Lagos, whereas in the northern windy stations usable electrical power ranges between 4.79 and 11.04 MW.

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Keywords: Renewable energy; winds profile; West Africa; surface characteristics; ERA interim; Weibull function.

1. INTRODUCTION

Energy from winds remains one of the viable options available in meeting ever increasing energy demand to drive the global economy. There are deliberate attempts to discourage energy production from fossil fuel because of environmental and global warming / climate change concerns. Investigation by Climate investment fund (CIF) shows that only one-fifth of the population of Sub-Saharan Africa has access to electricity, and many countries rely on inefficient, expensive, small-scale power generation that is oil based and contributes to climate change. Africa's chronic power problems affect 30 countries and take a heavy toll on economic growth and productivity [1].

In Nigeria, energy generation from wind is still at a developing stage, as there are no wind farms contributing to national grid [2]. The energy consumption mix in Nigeria is dominated by fuel wood (50.45%); petroleum products (41.28%) and hydro electricity (8%). Coal, Nuclear, geothermal, tidal, wind and solar energy are currently not part of Nigeria's energy mix, as they have either been neglected, not discovered or are currently at their early stage of development [3].

As much as 10 – 20 times hydro power exists in wind energy worldwide and if explored could probably supply up to 10% of global energy demand. [4], by assessing the wind power potential in two sites in south west Nigeria, has shown that the production of energy from winds appears promising. The study also emphasized the proposal which suggests that some Wind Energy Conversion Systems (WECS) can be deployed in these sites to generate substantial electricity with reasonably minimum operational cost. There are a number of reasons why power generation from wind should attract special attention in a developing nations like Nigeria. First, the quest for structural and economic development in the sub – Saharan Africa will require stable and reliable energy supply. Such 'luxury' is not available in sub – Saharan Africa, Nigeria inclusive, where epileptic power supply is placing unnecessary stress on industrial production.

Secondly, effective power generation from wind requires evaluation of winds regime and its characteristics which depends on the features of a proposed site. Wind regimes in Nigeria vary with seasons, topography and land use. Consequently, suitable site can only be found by carrying out thorough investigation of all possible sites. Furthermore, there are problems of inadequate data coverage; the networks of data available do not cover all potential sites. This limits previous studies to investigating few sites at a time which hinder drawing specific conclusions about available sites in Nigeria. Most of the regular stations are found at airports which do not represent the actual and typical wind farm. However, sites where actual measurements of wind speeds are not available can be covered with high resolution reanalysis data. Reanalysed data such as NCEP/ NCAR and ERA interim data are strongly influenced by observation and are therefore very suitable [5]. Finally, combining wind source with hydro power generation will hasten the attainment of self sufficient power development for most sub Saharan regional economies. Identifying potential sites for commercial and large scale wind farm requires comprehensive assessment of all potential sites in Nigeria. In most potential sites, surface winds measured and reanalysed at a height of 10 m are usually available. It required that wind speeds at the turbine hubs be estimated from the surface winds (height of 10 m). Generally, reasonable estimates are made when the site characteristics (e.g. Surface roughness and atmospheric stability) are taken into consideration. The aim of this study, therefore, is to explore all potential sites for wind energy generation in Nigeria taking into consideration specific site characteristics for efficient performance of WECS.

2. MATERIALS AND METHODS

Nigeria (the study area) is a tropical location which extends from the Atlantic coast in the south at latitude 4°N to the fringe of Sahel region in the north at latitude 14°N. The longitude stretches from 3°E to 15°E. The latitudinal extent places the study area under two wind regimes. The south westerly winds which flow over Atlantic Ocean into the area during the wet season from March to October are usually moist. Second wind regime (the north easterly winds) flows over the dry Sahel occupies the dry season from November to February of the following year [6]. Thus, the south receiving more rain is wetter than the north. This rainfall pattern is reflected in vegetation cover; south is dominantly forested ranging from mangrove at the coast to evergreen, deciduous tall tree in the rain forest while the north is covered by long grasses in the guinea savanna and short grasses in the Sudan savanna and fringe of Sahel savanna (Fig. 1). Variations in the vegetation, to large extent, account for variations in the roughness parameters and wind flow.

The main data used in this study consist of daily northward wind component (u) and eastward wind component (v) for year 2011 obtain from ERA interim reanalysed data set at reference height of 10 m. Others are the surface albedo and cloud cover for the same period. The data were extracted at resolution of 0.5^o longitude by 0.5^o latitude. The wind components are surface and single level parameters archived on the model's Gaussian grid; they are produced by either reanalysis (An), or forecast (Fc) [7]. For this study, the reanalysed set has been used because they are strongly influenced by observations (we compared the estimated wind speeds with the observed for some stations, the coefficients of correlation were >0.8, see Fig. 2). Wind speeds magnitudes at the reference height were resolved from the u and v components using the relationship: $U = \sqrt{u^2 + v^2}$ where U is the wind speed magnitude. Daily winds speeds were calculated for 39 selected stations shown in Fig. 3. We also present in Table 1, the basic meteorological parameters of the selected stations.

3. THEORY AND CALCULATIONS

Stronger winds are generated at higher heights where the influence of obstacles is minimized. Thus, turbine hubs are usually placed at height of about 70 – 80 m for effective power generation. From the surface wind speeds at 10 m, we estimated the wind at 70 m necessary for the calculation of wind power density in the study area.

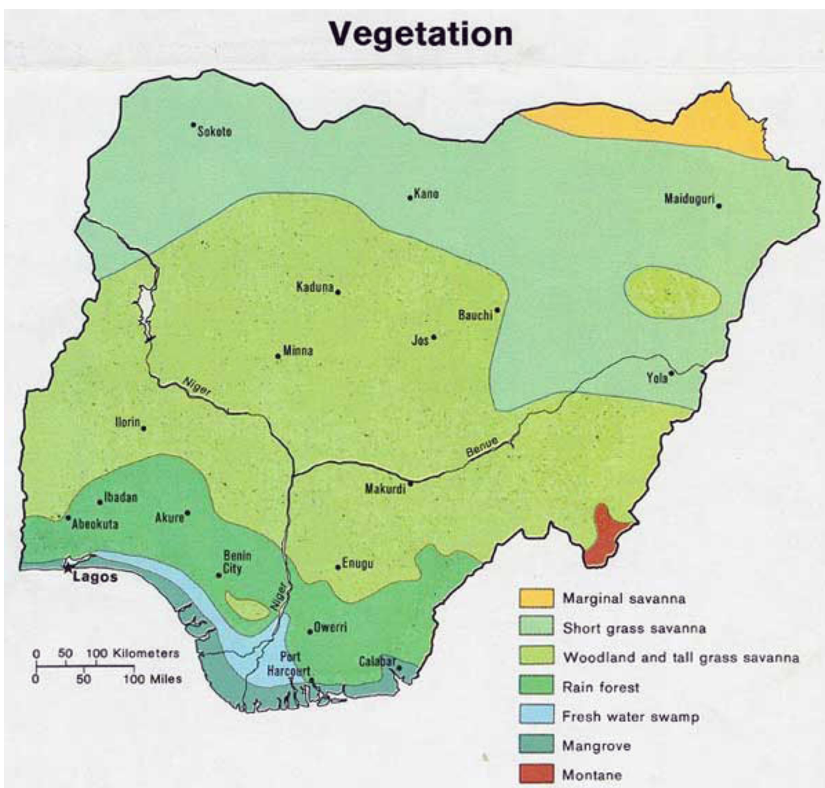


Fig. 1. Vegetation distribution in Nigeria. From south to north the vegetation can be broadly classified into coastal (mangrove, fresh water swamp), rain belt (rainforest), Guinea savanna (woodland and tall grass savanna, Montane), Sudan savanna (short grass savanna) and Sahel savanna (Maginal savanna)

Source: CBN (Central Bank of Nigeria). 1999. Annual report 1999. CBN, Lagos, Nigeria

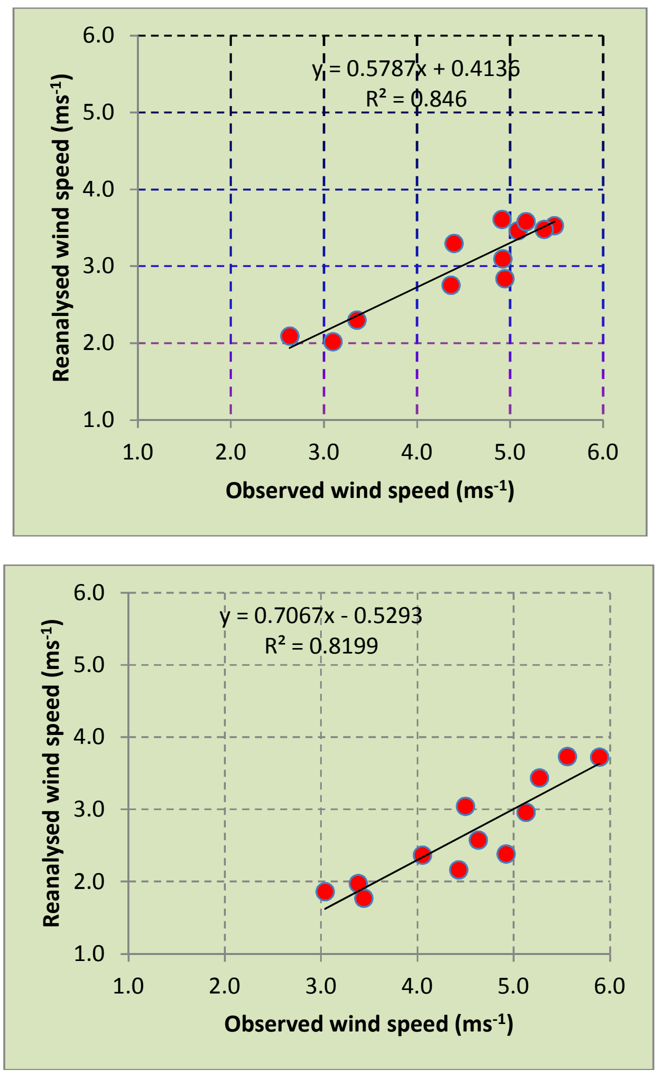


Fig. 2. Comparison between observed and reanalysed wind speeds for KAT and SOK

Table 1. Stations basic meteorological parameters, mean daily Albedo and cloud cover

Station name	Abbreviation	Longitude (°E)	Latitude (°N)	Mean height above sea level (m)	Mean Albedo	Mean cloud cover
Abeokuta	ABE	7.2	3.3	104.0	0.155	0.63
Abuja	ABU	9.3	7.0	343.1	0.157	0.52
Akure	AKU	7.3	5.3	375.0	0.154	0.61
Bauchi	BAU	10.3	9.8	609.7	0.189	0.41
Benin	BEN	6.3	5.1	77.8	0.096	0.70
Bida	BID	9.1	6.0	144.3	0.160	0.51
Birni Kebbi	BIR	12.5	4.2	220.0	0.220	0.36
Calabar	CAL	5.0	8.4	61.9	0.143	0.86
Enugu	ENU	6.5	7.6	141.8	0.152	0.70
Gusau	GUS	12.2	6.7	463.9	0.218	0.36
Ibadan	IBA	7.4	3.9	227.2	0.151	0.65
Ibi	IBI	8.2	9.8	110.7	0.160	0.57
Ijebu	IJE	6.8	3.9	77.0	0.151	0.65
Ikeja	IKE	6.6	3.3	39.4	0.061	0.59

Station name	Abbreviation	Longitude (°E)	Latitude (°N)	Mean height above sea level (m)	Mean Albedo	Mean cloud cover
Ikom	IKO	6.0	8.7	119.0	0.140	0.74
Ilorin	ILO	8.5	4.6	307.4	0.160	0.50
Jos	JOS	9.9	8.8	1290.0	0.187	0.42
Kaduna	KAD	10.6	7.5	645.4	0.190	0.42
Kano	KAN	12.1	8.2	472.5	0.231	0.33
Katsina	KAT	13.0	7.7	517.6	0.284	0.25
Lokoja	LOK	7.8	6.7	62.5	0.154	0.61
Maiduguri	MAI	11.9	13.1	353.8	0.216	0.29
Markurdi	MAK	7.7	8.5	112.9	0.160	0.57
Minna	MIN	9.6	6.5	256.4	0.160	0.51
Uguru	NGU	12.9	10.5	343.1	0.253	0.23
Ogoja	OGO	6.7	8.8	117.0	0.140	0.74
Ondo	OND	7.1	4.8	287.3	0.151	0.65
Onitsha	ONI	6.2	6.8	67.0	0.152	0.70
Oshogbo	OSH	7.8	4.5	302.0	0.151	0.65
Owerri	OWE	5.5	7.0	91.0	0.152	0.70
Portharcourt	POR	4.9	7.0	19.5	0.157	0.82
Potiskum	POT	11.7	11.0	414.8	0.228	0.32
Shaki	SHA	8.7	3.4	330.0	0.156	0.52
Sokoto	SOK	13.0	5.3	350.8	0.252	0.29
Uyo	UYO	5.5	7.9	38.0	0.152	0.70
Warri	WAR	5.5	5.7	6.1	0.150	0.74
Yelwa	YEL	10.9	4.8	244.0	0.178	0.42
Yola	YOL	9.2	12.5	186.1	0.159	0.45
Zaria	ZAR	11.1	7.7	110.9	0.190	0.42

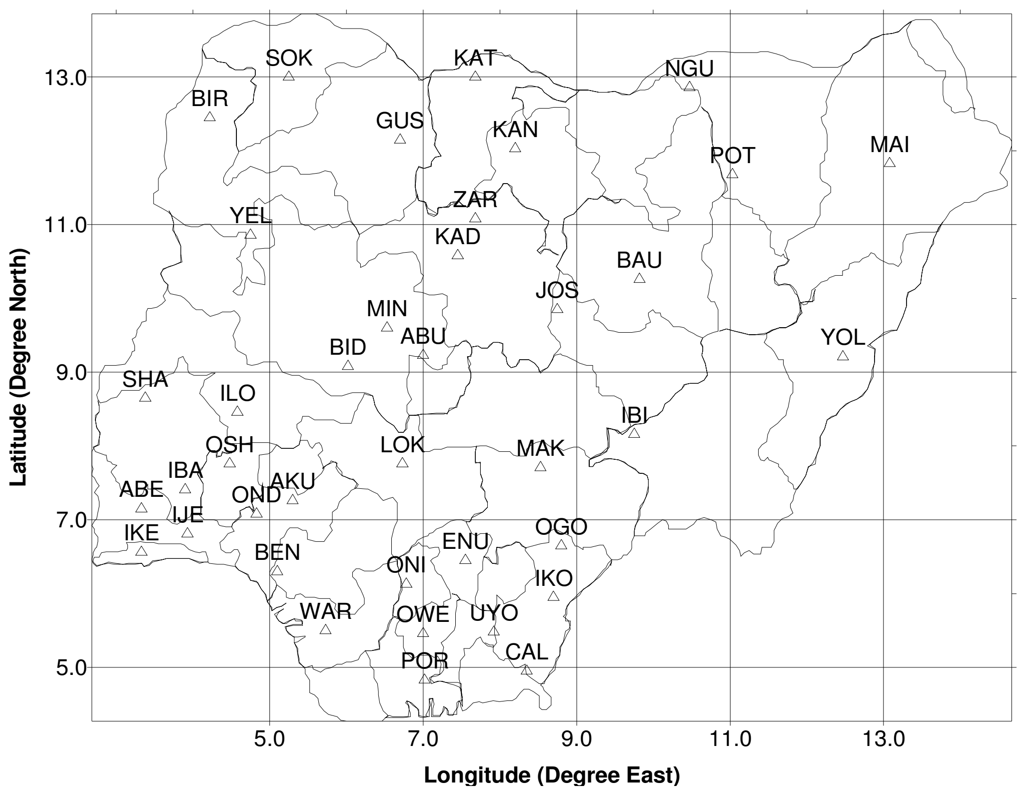


Fig. 3. Map of Nigeria showing the location of stations considered in this study. Stations abbreviation as contained in Table 1

3.1 Wind Speeds at Wind Turbine Height

Following [8] and [9] wind speeds at turbine hub were estimated from;

$$U_2 = U_1\left[ln\left(\frac{z_2}{z_0}\right) - \varphi_m\left(\frac{z_2}{L}\right)\right] / \left[ln\left(\frac{z_1}{z_0}\right) - \varphi_m\left(\frac{z_1}{L}\right)\right] \quad (1)$$

where U_1 and U_2 are the wind speeds at heights z_1 and z_2 respectively, L is the Monin-Obukov length and for unstable condition, the stability correction function is;

$$\varphi_m\left(\frac{Z}{L}\right) = 2ln\left(\frac{1+\mu}{2}\right) + ln\left(\frac{1+\mu^2}{2}\right) - 2tan^{-1}(\mu) + {}^{\pi}/_{2}$$

$$\mu = \left(1 - 16\left(\frac{Z}{L}\right)\right)^{\frac{1}{4}}$$

For stable condition $\varphi_m\left(\frac{z}{L}\right) = 4.7z/L$

Equation [1] expresses the relationship between horizontal wind speeds at two levels which takes into account the contribution of stability to the wind flow (stability depends on surface characteristics and roughness parameter). Application of this equation requires that the value of Monin – Obukov length be known. Estimates of L which include calculating friction velocity u_* are found by iteratively solving equations [2] and [3] until the successive values of L do not change by more than 5 % as follows.

$$L = \frac{\rho C_p T_{ref} u_*^3}{kgH} \quad (2)$$

$$u_* = \frac{kU}{\ln\left(\frac{z_{ref}}{z_o}\right) - \varphi_m\left(\frac{z_{ref}}{L}\right) + \varphi_m\left(\frac{z_o}{L}\right)} \quad (3)$$

where acceleration due to gravity (g = 9.8 ms^{-2}), C_p is specific heat of air at constant pressure, ρ is density of air, and k is the von Kármán constant, equal to 0.4. We make initial guess for u_* by setting L = ∞ in equation [3], which is a necessary condition for neutral stability. The sensible heat flux (H) was obtained using equation (4) [10];

$$H = \frac{0.9R_n}{1+\frac{1}{\beta}} \quad (4)$$

R_n is net radiation and β is Bowen ratio. R_n is calculated from;

$$R_n = \frac{(1-r)R + c_1 T_{ref}^6 + \sigma_{SB} T_{ref}^4 + c_2 n}{1+c_3} \quad (5)$$

where $c_1 = 5.31\times10^{-13}$ Wm^{-2}K^{-6}, c_2 = 60 Wm-2, c_3 = 0.12, $\sigma_{SB} = 5.67\times 10^{-8}$ Wm^{-2} K^{-4}, T_{ref} is the temperature at reference height, and n is cloud cover, r represents the surface albedo and R is the solar radiation corrected for cloud cover:

$$R = R_o(1 - 0.75n^{3.4})$$

R_o is the clear-sky insolation (Wm^{-2}) given by $R_o = 990sin\varphi - 30$, where φ is solar elevation angle. Determination of local elevation angle is an easy task in geometry following [11] and [12]:

$$\varphi = sin^{-1}\left(sin\emptyset sin\delta - cos\emptyset cos\delta cos\left[\left({}^{\pi t_h}/_{12}\right) - \gamma_e\right]\right) \quad (6)$$

$\emptyset$ and γ_e are the latitude and longitude in radians, t_h is coordinated universal time in hours, δ is the solar declination angle which is calculated as;

$$\delta = \emptyset_r cos\left[{}^{2\pi(d-d_r)}/_{d_y}\right]$$

where $\emptyset_r$ is the latitude of Tropic of Cancer (23.45°), d is Julian day, d_r is the day of the summer solstice (173), and d_y is the average number of days per year (365.25).

3.2 Weibull Wind Speeds Density Distribution

Wind speed probability density function (PDF) can be reasonably approximated by the parametric Weibull distribution [13,14]. Although there are alternative parametric models to the Weibull function [15,16,17], the relative ease of computation and widespread application in wind systems assessment elicited the use of Weibull function in this study. The expression for two – parameter Weibull distribution is given as;

$$f(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} exp\left[-\left(\frac{U}{c}\right)^k\right] \quad (7)$$

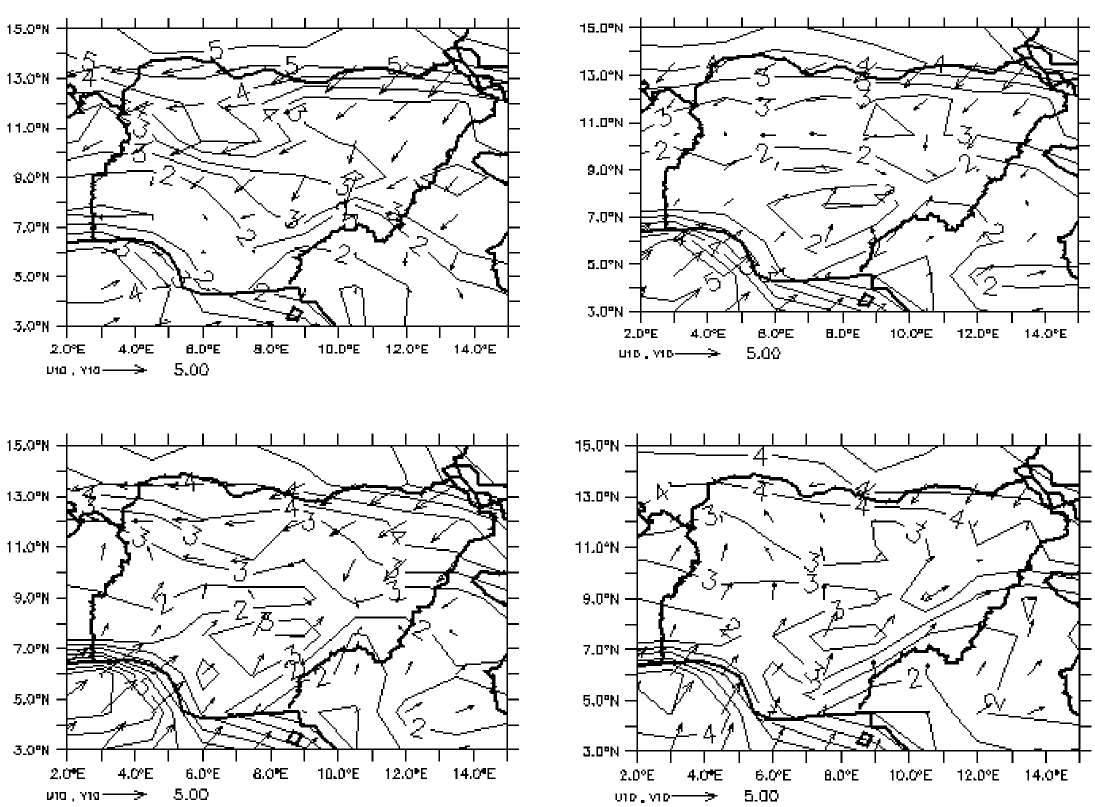
where k is the shape parameter and c is the scale parameter. The parameters were estimated using the maximum likelihood estimates (MLE) method of [18]. The wind power density (WPD) in watts per square meter is a function of wind speed PDF and is given by [19] as:

$$WPD = \int_0^\infty \frac{1}{2}\rho U^3 f(U)$$

4. RESULTS

4.1 Surface Wind Distribution

Monthly wind speeds distribution at the surface responds directly to the large scale monsoon flow over Nigeria as shown in Fig. 4. In January and February north easterly (NE) winds prevail over most of the stations but with stronger winds, about 5 ms^{-1}, over the northern stations. Evidence of weak (2 – 3 ms^{-1}) south westerly (SW) flow was observed over the coastal stations of, for example, Calabar, Warri and Portharcout. This situation persists in February and March except that the NE flow retreats while SW flow advances and becomes stronger from the rear. Months of March and April mark the onset of wet season and are characterized by convective (thundery) activities; the core, as shown by [20], is located at 100 km south of Intertropical continental zone (ITCZ). ITCZ is the surface meeting line of SW and NE winds. The distance of centre of thundery activities from ITCZ probably accounts for the rear strengthening of SW winds. In the wet months of April, May, June, July SW winds cover all the stations; however, the winds are not as strong as expected. In these months, the wind patterns are of monsoon type which are generally weak and devoid of thundery activities. The next two months (August and September) have weaker winds over all the stations except at the fringe of Sahel savanna. These months are characterized by short minimum rainfall period (or sometimes dry condition south of 10^{o}N) lasting between 3 to 5 weeks. This period marks the beginning of southward retreat of SW winds when, generally, there is subsidence leading to cloud growth suppression. In November and December, dry season is well established over the northern stations and once again, the winds are stronger under the influence of southward progressing NE winds regime. These seasons and wind regimes modulate the wind distribution and hence wind energy potential of all the stations as we shall show later. Estimated wind speeds at 70 m over Lagos, Bauch, Abuja, Enugu, Potiskum, for example, range between 7 and 15 ms^{-1}. On the extreme occasions wind speeds 20 ms^{-1} is also accessible.



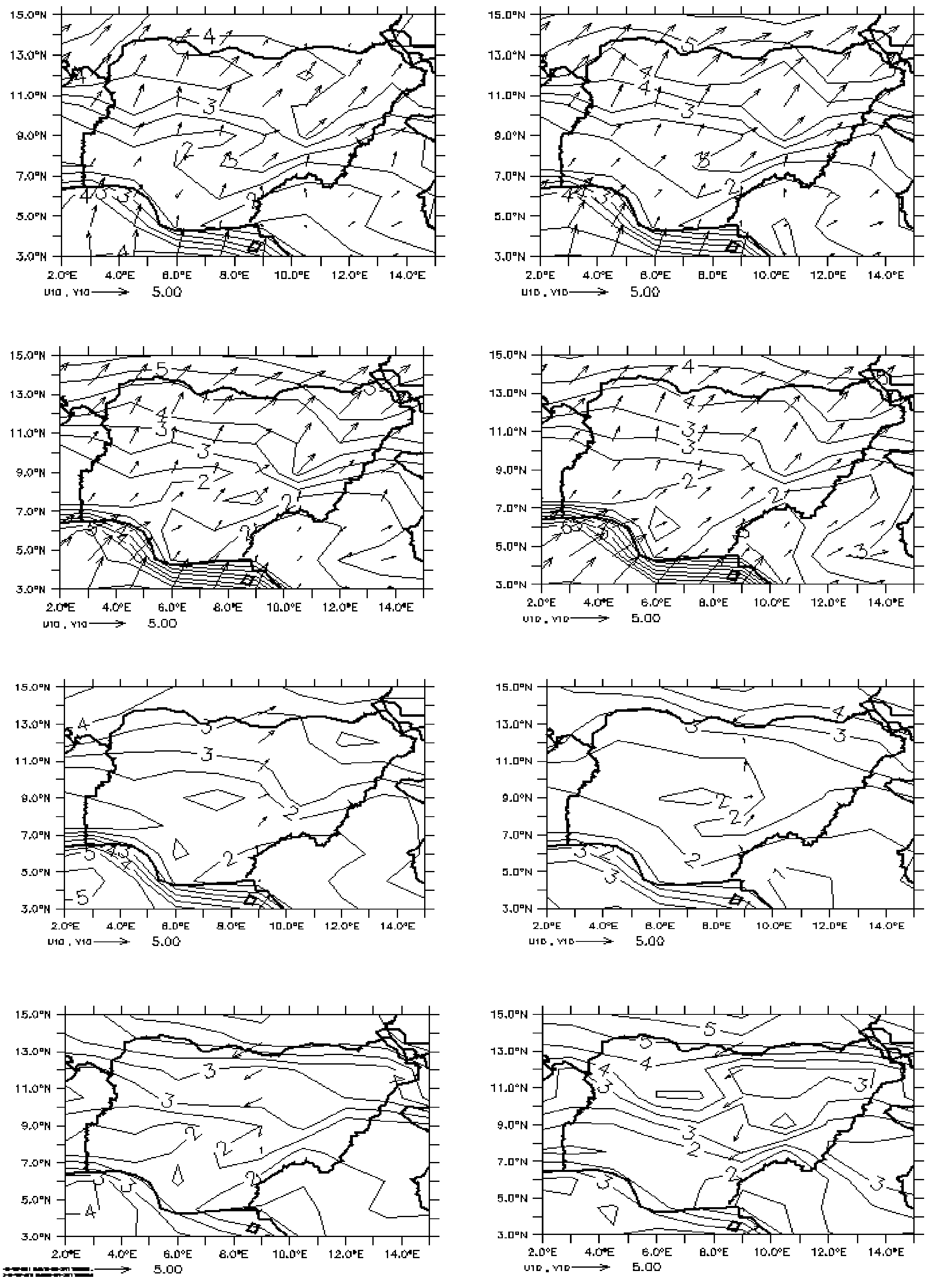
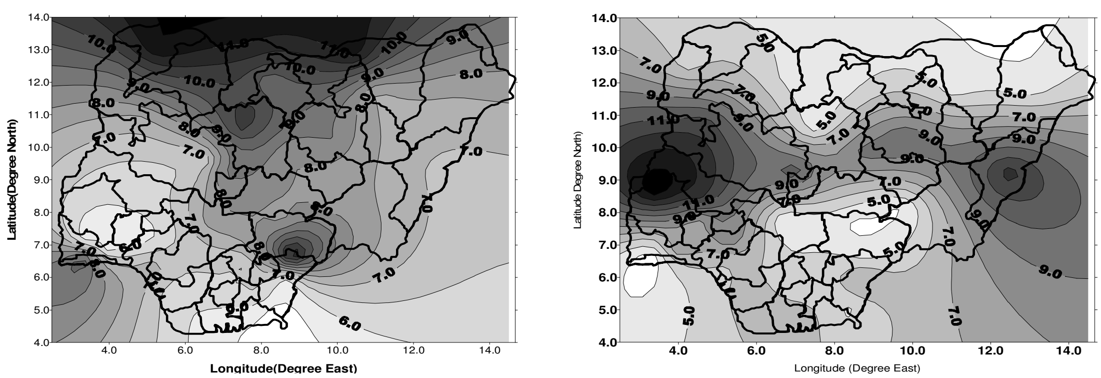


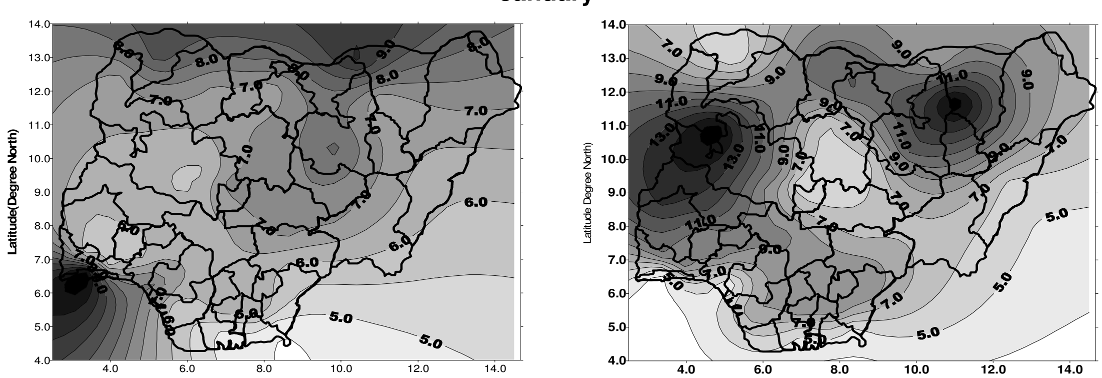
Fig. 4. Monthly Wind regime over Nigeria

4.2 Weibull Scale and Shape Parameters

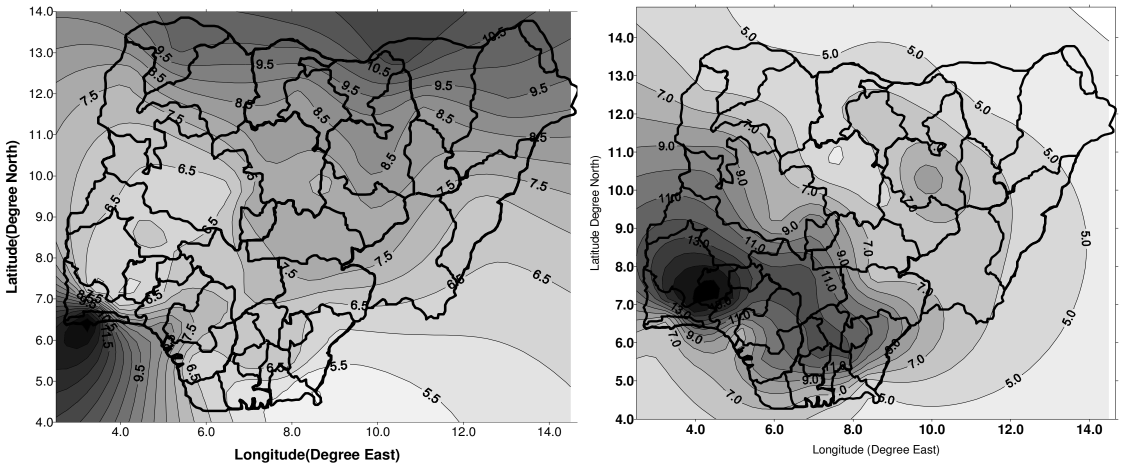
Consistent flow of wind throughout the year will be a prerequisite for an ideal location of potential wind farm. In other words, a site where there is persistent wind speeds greater than the cut –in speed of turbine blade will be a suitable location for commercial wind energy investors. One way of assessing potential site for sufficient winds is the use of shape and scale parameters of the parametric models such as gamma, normal, Weibull distributions etc. [21] investigating monthly rainfall in Africa using gamma function delineates as “shape dominated” (large k and small c) or “scale dominated” (small k and large c). Shape dominated regimes tend to define areas that typically received consistent rainfall accumulation in the historical record, and scale dominated areas have large variance in comparison to the mean. We extend same assertion to the winds regime over our stations. The distributions of scale and shape parameters magnitude in Fig. 5 are strongly influenced by periods and seasons of the year, it shows monthly variations as a function of location. In January shape parameter dominated over the extreme northern stations of Katsina, Sokoto, Nguru and part of Kano and Gusau. The domination of shape parameters in these locations is consistent with strong wind speeds over the stations in January. In addition to the extreme northern station, there are ‘inland’ (Ikot and Jos) and ‘coastal’ stations (Lagos) where local topographical features such as high altitude or sea breeze strengthens the wind speeds. Stations where shape parameter dominates have consistent high wind speeds, whereas, the rest receive sporadic high and low wind speeds in January. Persistence in wind speeds distribution in February is somewhat similar to that of January but with a lower magnitude of shape parameter over the stations. In March, the domination of scale parameter has shifted to the south western stations with extension to eastern stations, whereas, north eastern and extreme northern stations are consistently dominated by the shape parameter. This scenario persisted throughout the remaining months of the year with little variations. Generally, northern stations beginning from latitude 9°N have record of persistent wind speeds throughout the year when compared to station south of same latitude. The only exception is Lagos (Ikeja) where there is persistent high wind speeds perhaps due to direction of sea breeze wind flow over the station.



January



February



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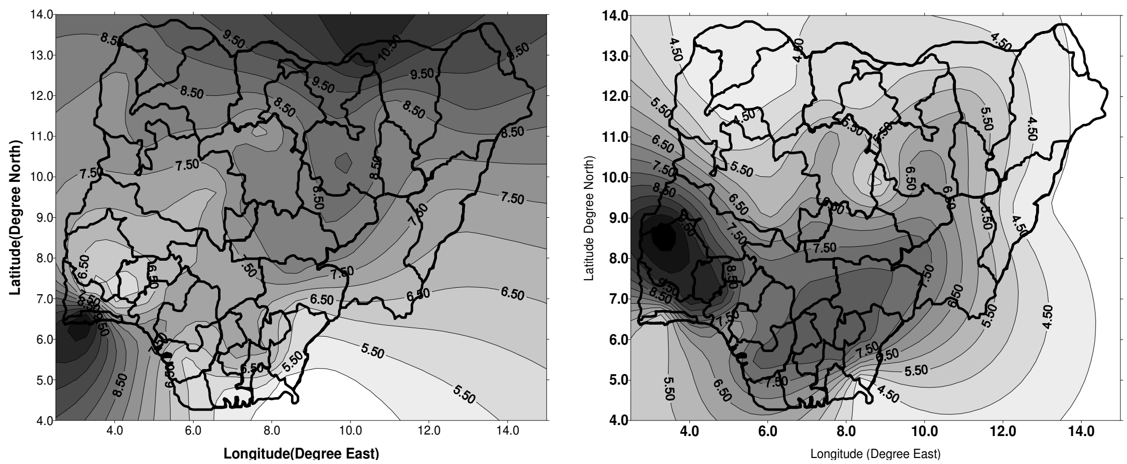
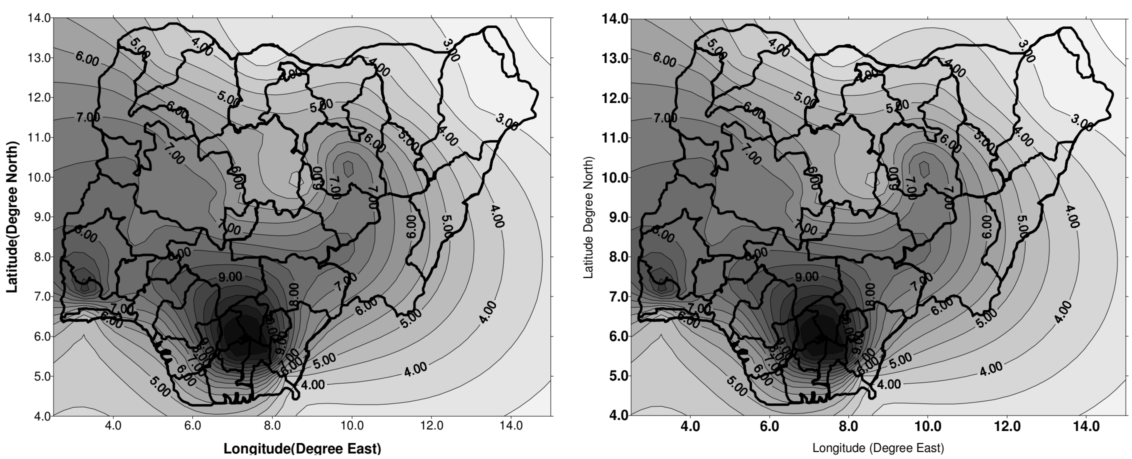
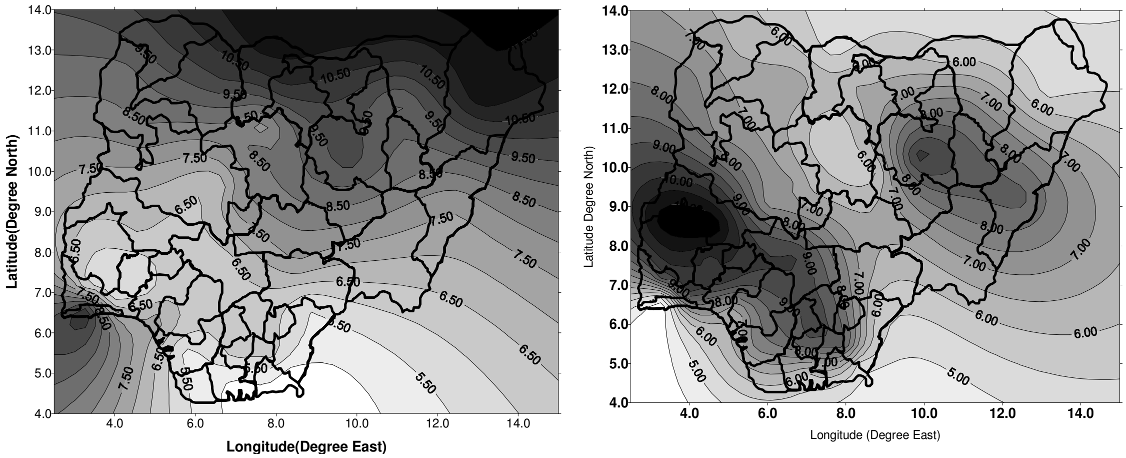


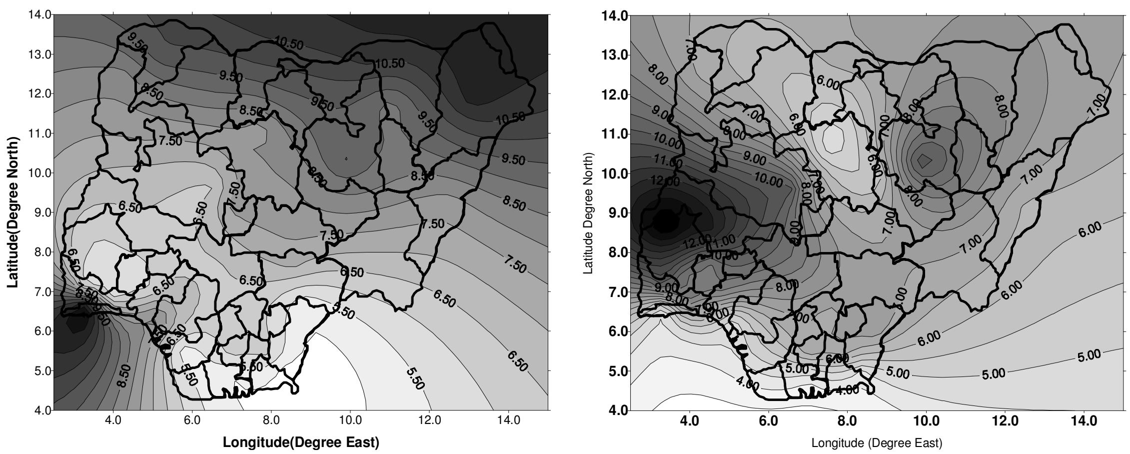
April



May



June



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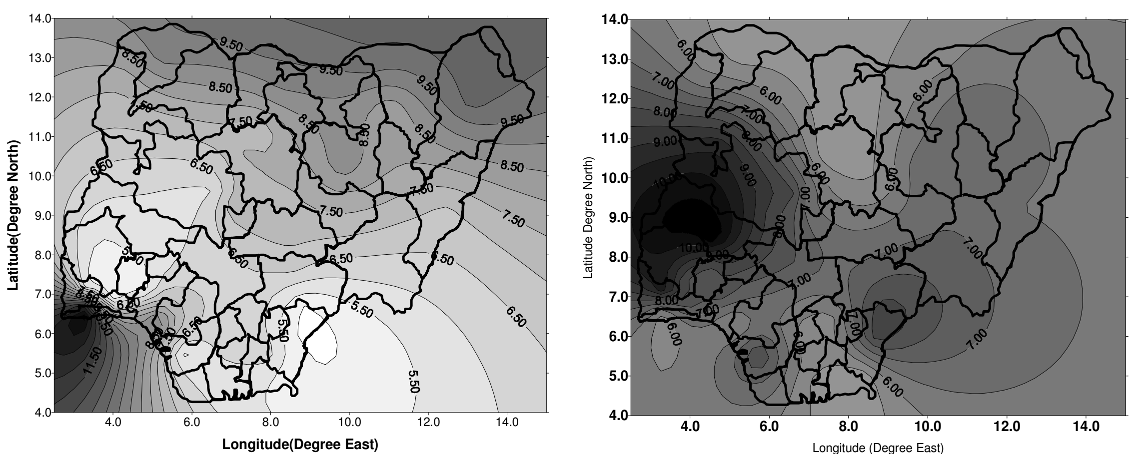
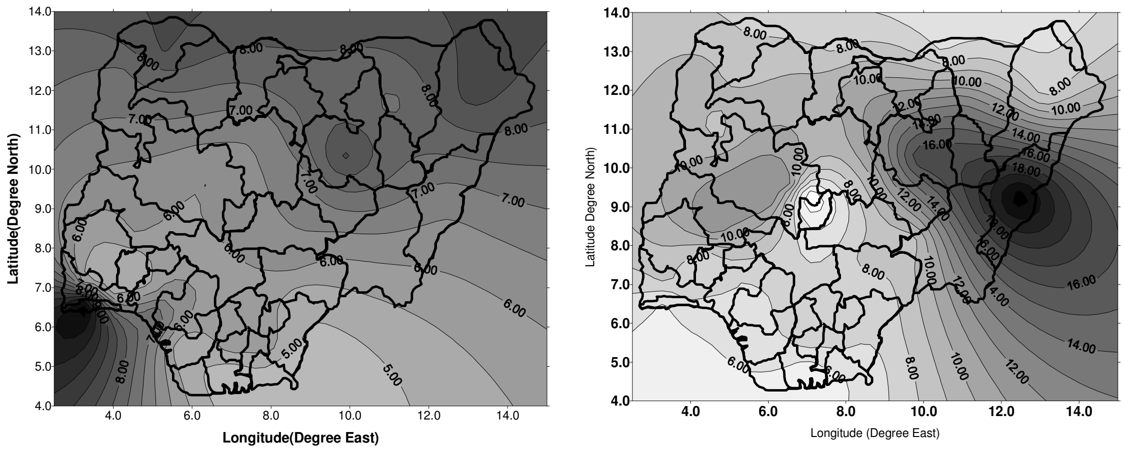
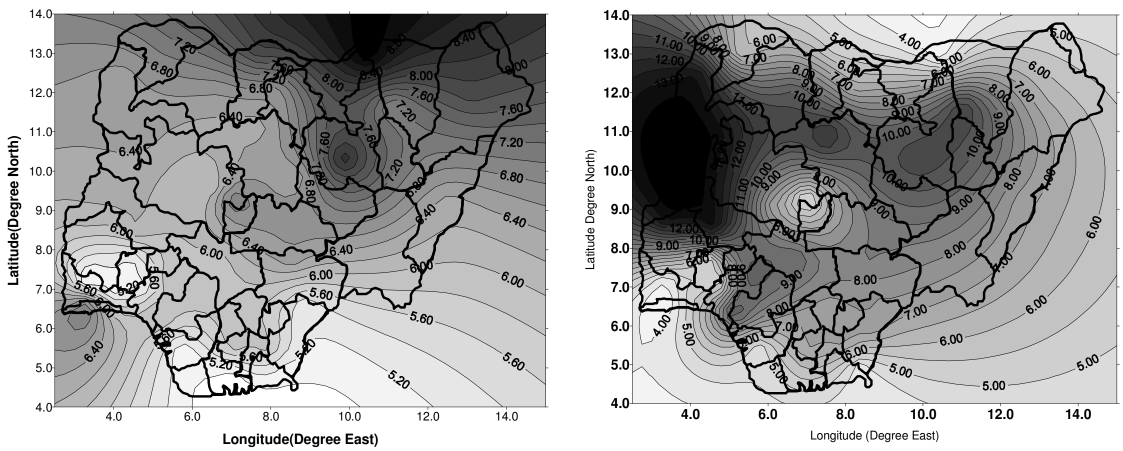


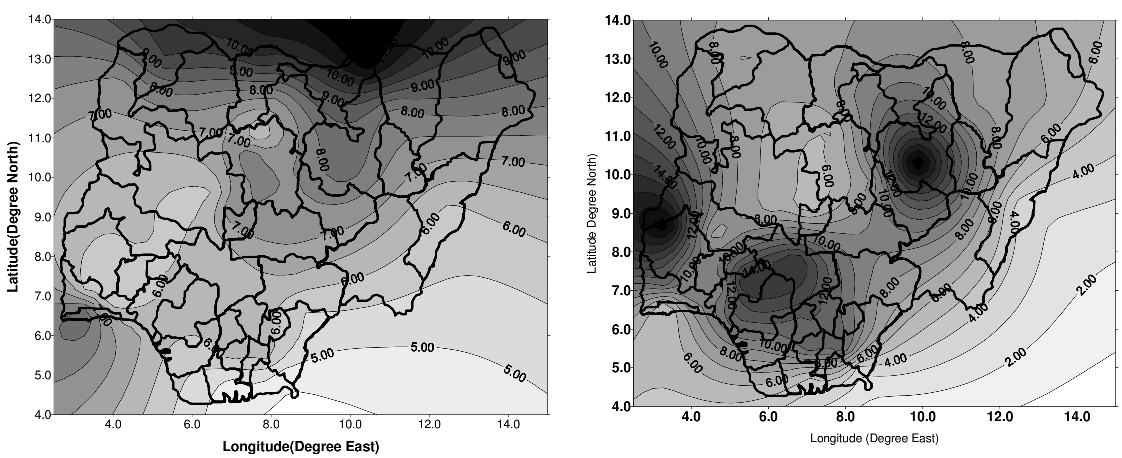
August



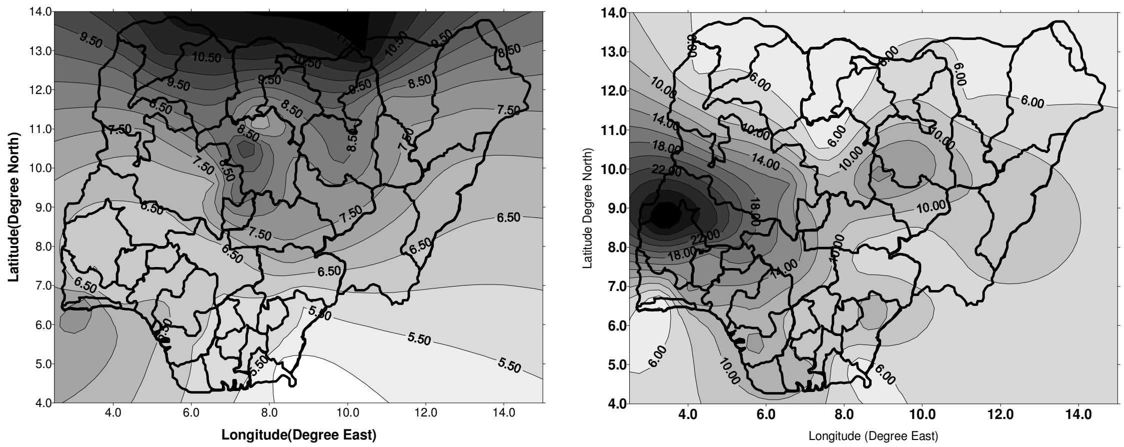
September



October



November



December

Fig. 5. Distribution of monthly values of shape parameter (left panel) and scale parameter (right panel)

4.3 Quarterly Total Power Density

The total quarterly power density at the turbine height of 70 m for each station was estimated as shown in Fig. 6. In the first three months of the year (JFM) highest total power density greater than 2.5 Kwm-^{2} can be generated in station like Abuja while the lowest (0.5 – 1 kWm^{-2}) can be obtained in the low wind areas of Portharcourt and Calabar. In the second quarter (AMJ) highest total power density centre has shifted to stations like Kaduna, Yelwa and Markurdi whereas Calabar station is still maintaining its lowest level of total power density. As we move from the second quarter to the third, the area of highest power density has shifted to the northern stations of Gusau, Kano, Nguru. The period coincides with time of lowest power density in the southern stations of Lagos (Ikeja), Warri and Shaki. In most of the stations in Nigeria, power density remains at an average of 1.5 kWm^{-2} in the last quarter (OND) of the year except in the low power density areas of Portharcourt and Calabar. In contrast, power densities in Potiskum, Sokoto and Bauchi are between an average of 2.5 and 3.5 kWm^{-2}. These stations, as expected, are in the northern fringe of the Sudan and Sahel savannas where the vegetation types are of short grasses.

4.4 Contingency of Usable Power Density

It is absolutely not possible for any turbine to generate power at all wind speeds. The amount of power generated by turbine depends on the available wind speeds within the range of cut – in and cut – out wind speeds of the turbine. Using the General Electric 1.5xle type turbine, usable power was calculated for selected stations and the contingencies are presented in Table 2. For Gusau, quarterly usable electrical power ranges between approximately 5 and 11 MW. For easy comparison, Z score of usable power has been calculated for the selected stations in each quarter of the year. Z score greater than 0.5 indicates that generate power is greater than the mean by half the standard deviation while Z score lesser than -0.5 means generated power is lesser than the mean by half the standard deviation. The Z scores between these upper and lower bounds are considered as within the range of mean usable power. Over Ikeja (Lagos), the probability of detection (PoD) of usable power around the mean throughout the year is 89.04 %. This is consistent with wind distribution over the station. Low wind areas such as Abuja and Enugu have PoD of 35.61 % and 49.86 % respectively. Common characteristics of high PoD stations is high quarterly Z score count throughout the year, which translates to existence of wind speeds close to mean wind speed for greater number of days in a year. Such stations will be most suitable for large scale wind farm.

5. DISCUSSION

Surface wind over Nigeria is generally low. However, when extrapolated to a height of 70 m, wind speeds strong enough to generate electricity can be obtained. While estimating the

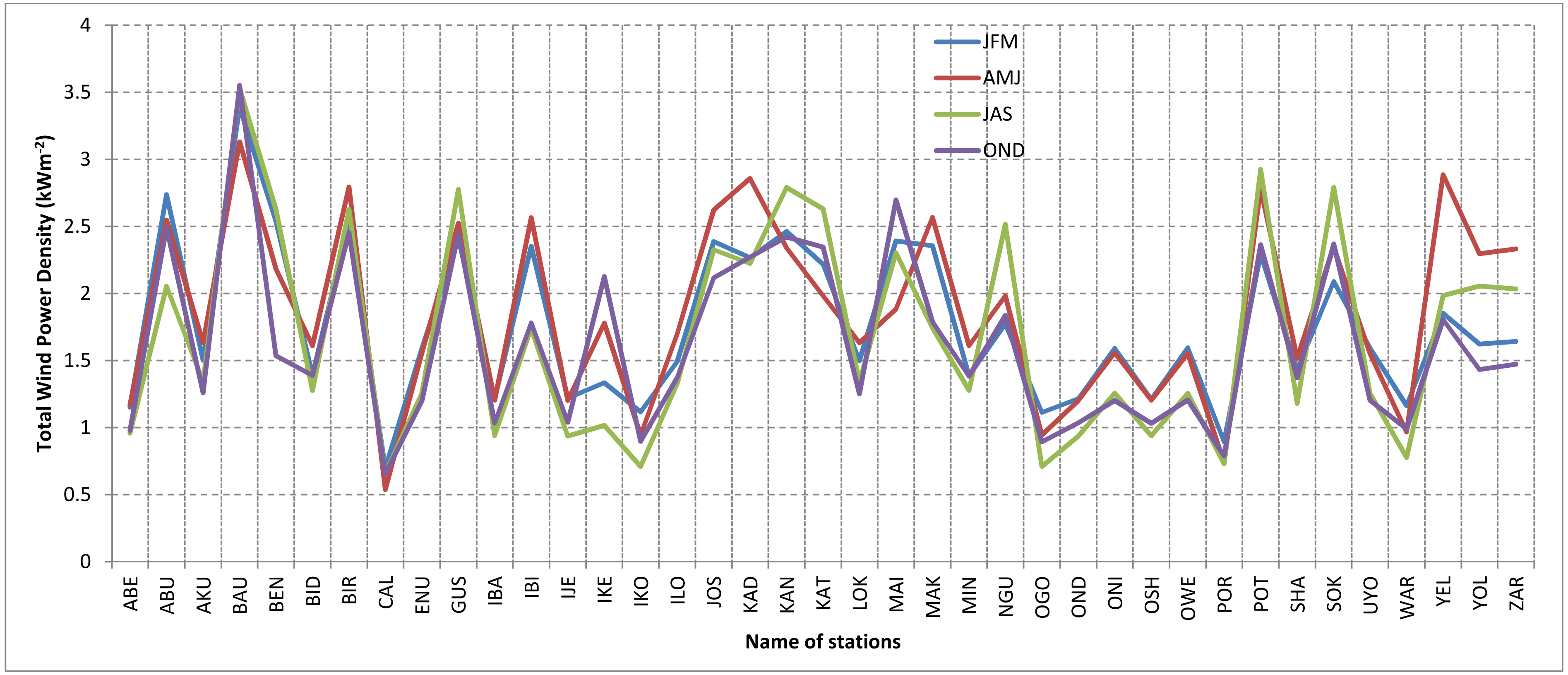


Fig. 6. Estimates of the total wind power density available in the stations based on the calculated wind speeds at the aerogenerator hub height of 70 m. the quarterly groups are January, February and March (JFM), April, May and June (AMJ), July August and September (JAS) and October, November and December (OND)

horizontal wind speeds at levels above the surface it is essential to consider the effect of surface friction and other topographic features. The combined effect is the stability correction which was carefully considered while estimating wind profile our stations. To determine the approximate wind speeds at the turbine height many researchers use different methods [22,23,24,25,8,4]. Power law is the most used method for this purpose. Power law relates the wind speeds to surface roughness, topography and atmospheric stability [26]. The fundamental deficiency of power law is its inability to transit from one atmospheric stability to another and there is tendency for over estimation of wind speeds [2]. We overcome this problem by applying Monin-Obukhov similarity function making use of 'in situ' atmospheric conditions and putting into consideration the surface albedo and cloud cover. Wind speeds generally increase with height over all the stations. For example, at 70 m over Ikeja, calculated wind speeds was stronger than at the surface ranging between 8 – 14 ms^{-1}. Stronger winds observed at such height over Ikeja for a greater number of days in the year, are considered to be strongly influenced by sea breeze front which flows into the station from adjacent Atlantic Ocean. Over the northern stations of Bauchi, Yelwa and Potiskum the wind speeds are particularly strong due to land surface characteristics. There are two reasons for the such wind strength over northern stations. First, short grasses in these stations offer minimum resistance to free flow of wind and secondly, land surface temperature during the day is usually very high compared to surface temperature of southern stations. The high temperature overlain by cold polar air aloft produces static instability within the boundary layer which enhances strong convection thereby reinforcing wind speeds strong enough to generate dust plume [27,28].

These relatively stronger wind speed areas showed weibull distributions that are persistently dominated by shape parameter. In order words, the stations are characterized by wind speeds 'clustering' around the mean throughout the year. Thus, in these stations, wind power generation will *always* close to the mean for *all seasons*. Shape dominated stations are found in the Sudan and Sahel savannas in northern Nigeria. While Lagos shows the same characteristic in the south apparently due to influence of wind flow from adjacent Sea. Jos, high altitude station, is fairly dominated by shape parameter. The high altitude provides necessary conditions for localised orographic rainfall with attendant strong winds. Ikom and Ogoja also exhibited shape dominated characteristics as a result of proximity to Cameroun Mountains located at the east of the stations. Wind flows over the mountains modify wind speeds over the stations. These stations are therefore potential locations for commercial wind farms.

Table 2a. Mean quarterly Usable Power (MUP) in mega watt (MW) for the selected stations

	Ikeja	Enugu	Gusau	Bauchi	Abuja	Jos
Q1	11.3	0.40	11.04	2.47	1.49	1.07
Q2	12.0	0.37	13.13	9.29	1.28	5.70
Q3	2.50	0.28	3.55	4.77	0.82	1.25
Q4	2.78	0.23	4.97	2.36	1.54	0.69

Table 2b. Contingency of Z score daily mean value of usable power density in some selected stations. The usable power density has been calculated for general electric 1.5xle type aerogenerator having cut – in speed (v_o), rated wind speed (v_1), cut-out – speed (v_2), and rated power of 3.5 ms^{-1}, 11.5 ms^{-1}, 20.0 ms^{-1} and 1500kW respectively

I. Lagos (Ikeja)

	Z >0.5	0.5≥ Z ≥-0.5	Z <-0.5	Total
Q1	10	80	0	90
Q2	7	84	0	91
Q3	10	82	0	92
Q4	13	79	0	92
Total	40	325	0	365

Probability of Detection (PoD) = 89.04%

II. Enugu

	Z >0.5	0.5≥ Z ≥-0.5	Z <-0.5	Total
Q1	12	57	21	90
Q2	16	46	29	91
Q3	14	53	25	92
Q4	30	26	36	92
Total	72	182	111	365

Probability of Detection (PoD) =49.86%

III. Gusau

	Z >0.5	0.5≥ Z ≥-0.5	Z <-0.5	Total
Q1	6	84	0	90
Q2	11	80	0	91
Q3	11	81	0	92
Q4	5	87	0	92
Total	33	332	0	365

Probability of Detection (PoD) =90.96%

IV. Bauchi

	Z >0.5	0.5≥ Z ≥-0.5	Z <-0.5	Total
Q1	11	61	18	90
Q2	16	42	33	91
Q3	14	52	26	92
Q4	16	57	19	92
Total	57	212	96	365

Probability of Detection (PoD) =58.08%

V. Abuja

	Z >0.5	0.5≥ Z ≥-0.5	Z <-0.5	Total
Q1	16	46	28	90
Q2	28	23	40	91
Q3	28	23	41	92
Q4	16	38	38	92
Total	88	130	147	365

Probability of Detection (PoD) =35.61%

VI. Jos

	Z >0.5	0.5≥ Z ≥-0.5	Z <-0.5	Total
Q1	13	46	31	90
Q2	11	80	0	91
Q3	9	83	0	92
Q4	22	36	34	92
Total	55	245	65	365

Probability of Detection (PoD) =67.12%

6. CONCLUSION

There are potential sites in Nigeria where wind energy can be harnessed on commercial scale, such sites can be found where local terrains interact and strengthen the wind flow of the area. Some of the suitable locations are Lagos, Ikom, Ogoja and all stations at the fringe of Sudan and Sahel savannas. However, we observed that all the stations in this category have wind strengthening local feature such sea breeze, mountain flow and strong boundary layer diurnal atmospheric instabilities. Therefore, in estimating wind speeds at turbine hub for electricity generation, it will be necessary to factor such local features into adopted expressions.

Having considered the local features, the results in this study showed that while wind speeds and electrical power density at some stations are inherently low in places like Calabar and Portharcourt, some areas in the south and particularly in the north holds promising potential for electrical power generation due to persistent wind flow. Power density from these potential site ranges between 2.5 and 3.5 kWm^{-2}, which translate to about between 0.4 and 11 MW approximate quarterly usable electrical power output. It can therefore be established that wind is a viable power generation option in Nigeria.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. CIF Climate investment funds. Energizing Sub-Saharan Africa; 2013. Available:https://www.climateinvestmentfunds.org/cif/node/3377 (Accessed 19/08/2013)
2. Oluleye A, Ogungbenro SO. Estimating the wind energy potential over the coastal stations of Nigeria using power law and diabatic methods. African Journal of Environmental Science and Technology. 2011;5(11):985-992.
3. Omokaro O. Energy development in a fossil fuel economy: The Nigerian experience. The report of a National Dialogue to Promote Renewable Energy and Energy Efficiency in Nigeria. 2008;55.
4. Ajayi OO, Richard O. Fagbenle, James Katende, Samson A. Aasa, Joshua O. Okeniyi. Wind profile characteristics and turbine performance analysis in Kano, north-western Nigeria. International Journal of Energy and Environmental Engineering. 2013;4:27.
5. Ruprecht E, Kahl T. Investigation of the atmospheric water budget of the BALTEX area using NCEP/NCAR reanalysis data. Tellus. 2003;55A:426–437.
6. Oluleye A, Akinbobola A. Malaria and pneumonia occurrence in Lagos, Nigeria: Role of temperature and rainfall. African Journal of Environmental Science and Technology. 2010;4(8):506-516.
7. Berrisford P, Dick Dee, Keith Fielding, Manuel Fuentes, Per Kållberg, Shinya Kobayashi, Sakari Uppala. The ERA-Interim archive Version 1.0. ERA Report Series; 2009. Available:http://www.ecmwf.int/publications
8. Van Wijk AJM, Beljaars ACM, Holtslag AAM, Turkenburg WC. Evaluation of stability corrections in the wind speed profiles over the North Sea. Journal Wind Engineering Industrial Aerodynamics. 1990;33:551–566.
9. Stull R, Ainslie B. A simple model for pollution dispersion in a convective boundary layer. Journal of Applied

Meteorology and Climatology. 2006;45: 1727–1743.
10. Cimorelli AJ, Perry SG, Venkatram A, Weil JC, Paine RJ, Wilson RB, Lee RF, Peters WD. AERMOD description of model formulation. U.S. Environmental Protection Agency Rep. 2004;EPA-454/R-03-004:91.
11. Zhang D, Anthes RA. A high resolution model of the planetary boundary layer – sensitivity test and comparisons with SESAME - 79 data. Journal of Applied Meteorology. 1982;21;1594–1609.
12. Stull. Introduction to boundary layer meteorology Kluwer Academic, Dordrecht; 1988.
13. Ramirez P, Carta JA. Influence of the data sampling interval in the estimation of the parameters of Weibull wind speed probability density distribution: A case study. Energy Conversions Management. 2005;46:2419–2438.
14. Monahan AH. The probability distriburion of sea surface wind speeds. Part ii: Dataset intercomparison and seasonal variability. Journal of Climate. 2006;19: 521–534.
15. Jaramillo OA, Borja MA. Wind speed analysis in La Ventosa, Mexico: A bimodal probability distribution case. Renewable Energy. 2004;29(10):1613–1630.
16. Yilmaz V, Celik HE. A statistical approach to estimate the wind speed distribution: The case of the Gelibolu region. Dogus Universitesti Derg. 2008;9:122–132.
17. Morrissey Mark l, Werner E. Cook, Scott Greene J. An improved method for estimating the wind power density distribution function. Journal of Atmospheric and Oceanic Technology. 2010;27:1153–1164.
18. Davidian M, Giltinan DM. Nonlinear models for repeated measurement data. Chapman & Hall, First Edition; 1995.
19. Li M, Li X. MEP-type distribution function: A better alternative to Weibull function for wind speed distribution densities. Metrika. 2005;37:321–343.
20. Odumodu LO. Rainfall distribution, variability and probability in plateau–state, Nigeria. Journal of Climatology. 1983;3: 385–393.
21. Husak GJ, Michaelsen J, Funk C. Use of gamma distribution to represent monthly rainfall in Africa for drought monitoring applications. International Journal of Climatology. 2007;27:935–944.
22. Monteith JL. Principles of environmental physics. Edward Arnold, London; 1973.
23. Peterson EW, Hennessey JP. On the use of power laws for estimates of wind power potential. Journal of Applied Meteorology. 1978;17:390-394.
24. Leon S. On the mean vertical extrapolation of mean wind power density. Journal of Applied Meteorology. 1979;19:488–493.
25. Panosky HA, Dutton JA. Atmospheric turbulence. Wiley, New York; 1984.
26. Barbara GB, Richard WK, Murphy AH. Time series models to simulate and forecast wind speed and wind power. Journal of Climate and Applied Meteorology. 1984;23:1184–1195.
27. Alfaro SC, Gomes L. Modelling mineral aerosol production by wind erosion: Emission intensities and aerosol size distributions in source areas, Journal of Geophysical Research. 2001;106(D16): 18,075–18,084.
28. Karam Bou D, Flamant C, Tulet P, Chaboureau JP, Dabas A, Todd MC. Estimate of Sahelian dust emissions in the intertropical discontinuity region of the West African Monsoon, Journal of Geophysical Research. 2009;114:D13106. DOI: 10.1029/2008JD011444

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