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Assessment of the Offshore Wind Speed Distributions at Selected Stations in the South-West Coast, Nigeria

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Abstract- This paper assessed the offshore wind speed distributions at 10 m height in the southwest coast of Nigeria using a high-resolution satellite observations at 0.25° spatial grid resolution. Satellite wind speed and direction recorded over a 10-year period (2002–2011) were derived from the CCMP L3.0 data wind. The monthly, seasonal and annual wind characteristics for energy conversion based on three probability distributions were assessed. The Rician and Weibull models gave better fitting of the offshore wind speed at the southwest coast compared to the Rayleigh model. Results also revealed that the monthly mean wind speed variation exhibits a rather non-monotonic trend across different grid points driven by changes in the weather system activities while further investigation reveals higher wind speed and power density at the coastal region than over land in the northern Nigeria. The monthly mean wind speed recorded at the coastal region ranges between 4.99 and 5.56 m/s, 5.32 m/s for the interannual mean wind speed with the summer (JJA) and autumn (SON) mean wind speed distributions ranging from 6.11–6.76 m/s and 4.86–6.17 m/s, respectively, at a 10 m height asl. The coastal wind speed distributions show that offshore energy conversion at the southwest region of Nigeria is viable.

Keywords: Offshore wind atlas, Rician distribution, ECMWF reanalysis, satellite observed wind, Nigeria.

1. Introduction

For sustainable energy utilization and optimum wind farm layout, the near-surface annual wind speed distribution and the cause of wind speed slowdown have been investigated in literature [1-2]. Most of the observed wind stilling, decrease in the near-surface wind speed and the misrepresentation of the wind climates across various grid locations were linked to the local topography (such as vegetation and the density of the surface roughness elements) in the near surface wind field of an observing station [3-4]. Thus, this influences the wind flow across reference station and causes surface wind speed and direction perturbations in the lowest boundary layer.

In another literature, the slowdown of the near-surface wind speed observations was attributed to changes in: synoptic weather system activities as a result of the impact of climate change [7], atmospheric circulation pattern at a high altitude [5-6], among others. In few more energy studies, the cause of near-surface wind speed slowdown has been investigated in literature based on the annual and seasonal trends of local wind speed. From the wind study carried out in China for the period of 1956–2004, a decrease in the surface mean wind speed was attributed to North–South warming gradient in winter and the sunlight dimming caused by the air pollution lingering across the central areas in summer [8-10]. A decrease in the surface wind speed was also observed across Netherlands [11], Australia [12] and most of the areas in the Czech Republic [13]. For the Mediterranean regions, the surface mean wind speed trends were recorded to be non-monotonic [14]. Hence, the findings of Vautard et al [2] based on the historical observed wind speed (1979-2008) across 822 in-situ stations in Northern Hemisphere suggest that the changes in the surface processes may have played a crucial role in the slowdown of surface annual wind speeds at different regions.

In another development, the analysis of annual mean wind speed trend for a period of 11 years (2004–2014) at Jumla, Nepal was carried out [15]. Above the surface, the annual mean wind speed at a 10 m was observed to be decreasing from 7.35 to 5.13 m/s as a result of effect of climate change.

Nigeria's renewable resources such as the hydro, biomass, solar and the wind (Northern region and SW coast) have enormous energy potential for: the mitigation of the climate change impact, socio-economic growth, sustainable energy generation and accessibility, among others. As a fast developing nation consisting of 180 million populace, a daily peak electricity generation of about 4000-5000 MW is recorded as compared to the total installed capacity of power plants estimated at 11,165.40 MW across various generating stations (such as Egbin, Afam, Geregu, Ibom, Alaoji, Okpai, Olorunsogo, Sapele, Kanji, among others). From, the two main energy sources of generation in the country: (i) thermal power turbine stations (such as Egbin at 1320 MW capacity; Sapele station at 1020 MW; among others) located in the south region close to the natural gas supply sources, and (ii) hydro power stations (Kanji, 800 MW; Jebba, 540 MW; and the Shiroro, 600 MW) located further North region of Nigeria. In addition, available electric power generation capacity was at 7,139.6 MW; current transmission capability was recorded at 7,000 MW while the national peak demand were forecasted at 17,520 MW [16]. Furthermore, the comparison of the peak electric power demand forecast on April 2015 (12,80 MW) with the current peak power demand forecast (17,520 MW) dated the 14th October, 2016 shows a significant increase in the nation's electricity demands at approximation of 36.8% due to spontaneous economic recovery; high population growth; commercial and industrial demands for higher share of electricity from the distribution companies and urbanization [17]. Notwithstanding, new transmission power lines across the six different geopolitical zones in the country are still under construction and is expected to interconnect all existing and newly built power generation stations to the national grid for reliable system operation and accessibility.

In an attempt to provide both short and long-term solutions to the nation's electrification challenges using the wind and solar as alternative electricity sources, several researchers have carried out preliminary studies on the surface wind characteristics at different heights in some selected locations across the nation based on the monthly and annual mean wind speed data obtained from the Nigerian Meteorological Agency (NIMET) [18-21, 24-27]. The wind speed or energy assessment was carried out basically with three statistical models (Gumbel, Rayleigh and the Weibull). To further assess the viability of the small and large-scale wind energy systems for onshore wind farm development in Nigeria, the cost analysis (econometric) of an electrical power generation using a levelized cost of energy (LCOE) and present value cost (PVC) method at few selected sites for a low to high wind speed values were also carried out [22-23, 28-29].

Okechukwu et al [18] carried out a statistical analysis with the monthly mean wind speed data collected at anemometer height (3.7 m) of an existing station in Port Harcourt, Rivers State. Based on the Rayleigh probability distribution with the logarithmic profile for vertical wind speed projection to 50 m height, the wind speed profiles were determined. Musa et al [19] statistically analyzed the monthly, seasonal and annual mean wind speed statistics for sizing of small–medium scale turbines at the considered heights. The monthly mean wind speed measurements at 10 m height for 9-year period (2003–2011) were obtained for Maiduguri station. The wind speed observations were vertically extrapolated to different heights (36.6, 50, 80, and 99 m) agl based on the power law and Weibull distribution function. Sanusi et al [20] investigated the potential of Lagos station for wind energy generation in the southwest region using the monthly mean wind speed at 10 m height agl (1999 –2009). The variations of the monthly and annual mean wind speed and power density at 20, 40 and 50 m heights were also analyzed with the power law and Weibull model. Medugu et al [21] assessed the wind energy potential at a 10 m height for Mubi station measurements in Adamawa State of Nigeria to compensate for electric power supply inadequacy from the Power Holding Company of Nigeria (PHCN). The monthly mean wind speed and power density were recorded at 3.44 m/s and 16.34 W/m^2, respectively, for Mubi station. Okeniyi et al [22] based on the Gumbel and Weibull probability distributions assessed the wind energy potential at three selected stations (Katsina in Northern Nigeria; Warri in Delta state of Southwestern; and Calabar in Cross River state of the southeastern Nigeria). The daily mean wind speed measurements from three cup-generator anemometer at 10 m for a 5-year period (2006-2010) were obtained and the electric power generation of the wind turbine systems at 10, 30, 50, 70, 90 and 110 m heights were analyzed. Fagbenle et al [24] assessed the energy potential of two selected stations in the northeast region (Potiskum in Yobe state and Maiduguri in Borno state) with the monthly mean wind speed records and a 2-parameter Weibull mode at 10 m height for a period of 21-year (1987–2007). In another development, Abur et al in their studies statistically analyzed the wind energy potential from the Weibull and Rayleigh models at four selected stations (Potiskum, Bauchi, Yola and Maiduguri) in the northeastern Nigeria [26]. Their studies were carried out basically with the monthly mean wind speed observations across the period of 1997–2012. Ajayi et al [27] statistically analyzed the wind speed profiles or characteristics at Kano synoptic station in Northwestern Nigeria based on 2-parameter Weibull model. The energy generation of potential five wind turbine systems was also assessed using the monthly mean wind speed data at a 10 m height for 21 years period (1987–2007). Also, Ajayi et al [28] assessed the wind resource potential as well as the cost benefit analysis of wind power generation for 10 selected stations in the southwest region. Based on 24 years (1987–2010) wind records at a 10 m height agl, the costs of electricity generation for all stations (Ikeja, Ibadan, Marina, Ijebu Ode, Oshogbo, Ekiti, Ondo, Akure, and Abeokuta) were analyzed. Ohunakin et al [29] carried out an assessment of the wind energy potential at Jos station in Plateau state as well as the economic evaluation of two commercial wind turbine systems using the PVC method. Oluyeye et al [30] focused their studies on two coastal stations for wind energy generation in Nigeria. For these stations (Lagos and Calabar), the monthly mean wind speeds recorded for 18 years period (1991–2008) were obtained at a 10 m height and extrapolated to 15, 20, 25…, 65 and 70 m heights using the power law and diabatic method.

Inaccessibility to historical wind records at different vertical levels across six geopolitical zones in the nation is a major contraint for researchers in providing accurate and sufficient energy resource map relating to the wind speed distribution and energy development. From the wind studied findings for different synoptic stations across the country, a low wind speed trends for small-scale generation and water pumping were reported for the southwest and gradually increases to a relatively high wind speed region for utility energy planning in the north region of Nigeria [38].

For proper implementation of renewable energy technologies into the national grid, as well as for secure energy supply and mix, this study assesses the offshore wind speed distributions at a 10 m height asl in the southwest (SW) coast of Nigeria. Although, the assessment of the onshore wind distributions across the Northern Nigeria have been the subject of debate over the past few decades and have been recommended for a large-scale energy conversion based on several findings in literature, however, no energy study has considered the offshore wind speed distribution and its suitability for energy development.

In this paper, the satellite observations with the Weibull, Rayleigh and Rician models for the offshore wind speed distributions over a period of 10-year are assessed. In addition, the connectivity of the surface wind speed across the land and coast using different data sources is investigated as possible answers to frequent questions often raised regarding the onshore and offshore wind speed and energy potential in Nigeria. Thus, this region is further investigated by analyzing the prevailing direction of the surface wind speed at 10 m height using (i) a high resolution satellite observations across the coast, and (ii) ECMWF operational analysis wind across the land. Hence, the aim of this preliminary study is to provide an outlook of the seasonal and annual wind speed distributions for a period of 10-year (2002-2011) at different station points for potential wind turbine sitting and energy utilization.

2. Data

Time series of satellite wind observations in gridded analysis (uwnd and vwnd) across the considered field in Nigeria (x_1 = 3.0°E/3.0°N; x_2 = 15.0°E/3.0°N; x_3 = 3.0°E/15.0°N; and x_4 = 15.0°E/15.0°N) for a period of 10-year were obtained at 10 m height. The geographical coordinates map of the wind vector field, the locations of the considered offshore stations (A-P) in Southwest Coast as well as the available satellite wind observations for this period (2002-2011) are summarized (Table 1 and Fig 1). The time series wind vector of the surface wind field were produced on regular grid resolution (0.25x0.25°) with a dimension of 4096, $n_x = n_y = 64$ in the longitudinal and latitudinal directions, respectively. Unlike the onshore and sea-based measurements mostly used in long-term wind energy assessment studies, the availability of high quality wind data in a short period of time from a dense network of synoptic stations is the main limitations for wind studies in Nigeria. Thus, the offshore wind observations were sourced from a cross-calibrated multi-platform (CCMP) L3.0 dataset and contain a value-added 6-hourly gridded analysis of the ocean surface wind vector at four temporal resolution (00:00, 06:00, 12:00 and 18:00 UTC).

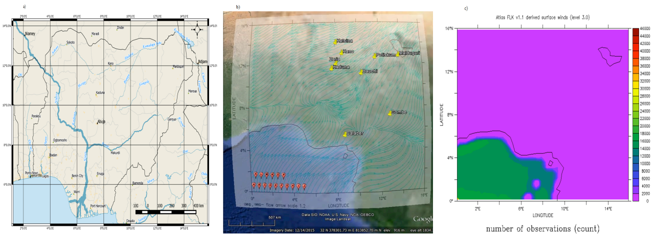

Fig. 1: (a) Geographical coordinates map of Nigeria **(b)** locations of the selected offshore stations (A-P) and the onshore **(c)** satellite number of observations across Nigeria for period of 2002–2011

The CCMP L3.0 datasets comprise of the cross-calibrated satellite ocean winds derived from remote sensing systems, RSS, (such as the SSM/I, SSMIS, AMSR-E, TRMM TMI, SeaWinds, QuikSCAT, WindSat and other available satellite instruments) using variational analysis method (VAM). With a cross-calibrated sea-surface emissivity model function which improves the consistency between local wind speed retrieval from the microwave radiometers (SSM/I, SSMIS, AMSR, TMI and WindSat) and the scatterometers (such as QuikSCAT and SeaWinds), a high-resolution (0.25°) gridded analysis ocean surface wind at 10 m height was derieved [31-32]. That is, MW satellite observed winds utilized for a particular CCMP grid point across the entire ocean wind field were basically derived from the passive instruments, and exceptions for the satellite ocean winds that come from the scatterometer (QuikSCAT, between the period of August 1999 and November 2009) with an approximation of twice per day observations (i.e, 12 hourly).

Satellite wind observations were continuously sensed by the remote instrument (RSS) across the ocean surface field but are non-available across the land (see Fig 1c) and at any grid location close to the coastline (< 50 km). Hence, the operational analysis wind field at 0.25° spatial grid resolution from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used in the VAM for producing the surface wind across the land and at any grid point where the cross-calibrated satellite observations were not available [33]. At a given time across the coastal region of Nigeria, the number of satellite observations range from the values of 1–5. Fig. 1c and Table 1 summarized the total number of available satellite ocean wind and the missing observations for a period of 10 years across the selected offshore/onshore stations in Nigeria.

A total number of 233, 728 wind speed data points were retrieved from the CCMP L3.0 winds at 10 m height for 16 offshore stations (A–P), of which 66.05 % were satellite wind observations while 33.95 % were missing for the whole period of 10 years. For land-based stations (Bauchi to Zaria) with non-existence of satellite observations, the surface wind records were basically derived from ECMWF operational analysis wind. Finally, integrated surface hourly wind speed and direction at 10 m agl for the land-based weather stations' platform for the same period were also sourced from the archive of National Climatic Data Centre (NCDC) Airways database [34]. Quality control was carried out on the wind observations to identify any offset, data error or missing data point at a given time.

Table 1. Coordinate systems, elevations and satellite number of observations for the selected station grids at the offshore and across the land (see Fig. 1b)

Station IDs.	Longitude (°E)	Latitude (°N)	Elevation (m)	Total no of satellite observations	Total no of missing observations
Offshore					
A	0.375	0.375	-4895.9	10,055	4,553
B	0.875	0.375	-4833.8	9,880	4,728
C	1.375	0.375	-4698.0	9,918	4,690
D	1.875	0.375	-4615.9	9,894	4,714
E	2.375	0.375	-4333.9	9,757	4,851
F	2.875	0.375	-4391.2	9,805	4,803
G	3.375	0.375	-4300.2	9,718	4,890
H	3.875	0.375	-4144.0	9,523	5,085
I	4.375	0.375	-4000.8	9,641	4,967
J	4.875	0.375	-3968.1	9,598	5,010
K	0.625	1.375	-4778.2	9,577	5,031
L	1.125	1.375	-4767.6	9,448	5,160
M	1.625	1.375	-4652.2	9,441	5,167
N	2.125	1.375	-4626.8	9,441	5,167
O	2.625	1.375	-4424.2	9,342	5,266
P	3.125	1.375	-4317.8	9,342	5,266
Onshore					
Bauchi	9.817	10.283	609.0	-	14,608
Kaduna	7.320	10.696	631.9	-	14,608
Kano	8.200	12.050	476.1	-	14,608
Katsina	7.683	13.017	517.0	-	14,608
Maiduguri	13.083	11.850	344.0	-	14,608
Potiskum	11.033	11.700	414.0	-	14,608
Calabar	8.347	4.976	64.0	-	14,608
Gombe	11.150	10.283	505.0	-	14,608
Zaria	7.686	11.130	661.4	-	14,608

3. Methodology

For wind energy assessment, the knowledge of the duration and distribution of the local wind speed across a region are essential. For analysis of the monthly, seasonal and annual wind speed distributions as well as the energy densities at each selected virtual station point (Fig. 1b), the surface wind field is horizontally interpolated to the station coordinates (Cols 2-3 of Table 1). That is, the horizontal interpolation of the zonal (uwnd) and meridional (vwnd) surface wind field to each station coordinates is carried out with the bilinear method instead of the nearest neighbor or linear interpolation technique.

The local wind speed and direction at 10 m height for each station grid coordinates are calculated from the bilinear interpolated wind speed vector based on the expression:

$$v(\theta) = \sqrt{\left[(uwnd(\theta))^2 + (vwnd(\theta))^2\right]} \quad (1)$$

where $v(\theta)$ denotes the calculated wind speed at a 10 m asl, the zonal and meridional wind speeds are given as $uwnd(\theta)$ and $vwnd(\theta)$, respectively.

Next, the time series of the wind speed and direction are grouped into the seasonal winds as function of the location of the station grid coordinates on the earth surface (Table 2).

3.1. Weibull Density Function

The variations of the local wind speed over the land and sea have been well described in literature based on different statistical models (Weibull, Rayleigh, Gumbel, Lognormal, Gamma and Logistic). Among these statistical models, the Weibull and Rayleigh models have been widely utilized in wind energy analysis.

Table 2: Classification of the offshore winds based on the seasonal lag at temperate and polar regions.

Seasons	Northern Hemisphere	Southern Hemisphere
Summer	June, July and August	December, January and February
Autumn	September, October and November	March, April and May
Winter	December, January and February	June, July and August
Spring	March, April and May	September, October and November

The interannual and seasonal wind speed variations caused by the changes in the large-scale atmospheric circulation as well as surface roughness elements are characterized by a 2-parameter Weibull and Rician probability density function (pdf). For the pdf, this is given:

$$f(v,k,c) = \left(\frac{k(\theta)}{c(\theta)}\right)\left(\frac{v(\theta)}{c(\theta)}\right)^{k(\theta)-1} \exp\left[-\left(\frac{v(\theta)}{c(\theta)}\right)^{k(\theta)}\right] \quad (2)$$

where *f(v,k,c)* is the probability of an observing offshore wind speed, v (m/s); θ is the prevailing wind direction; $k(\theta)$ and $c(\theta)$ are the sectorwise shape and scale (m/s) parameters, respectively, of the Weibull distribution.

Similarly, the cumulative probability function, *F(v,k,c),* of the Weibull distribution is expressed:

$$F(v,k,c) = 1 - \exp\left[-\left(\frac{v(\theta)}{c(\theta)}\right)^{k(\theta)}\right] \quad (3)$$

The mean value of the sectorwise observing wind speed, $v_m(\theta)$, is computed as:

$$v_m(\theta) = c(\theta)\Gamma\left[1+\left(\frac{1}{k(\theta)}\right)\right] \quad (4)$$

where Γ(.) denotes the gamma function of (.).

Putting $k(\theta) = 2$ into Eqs. (2) and (3), the Rayleigh density function of a continuous distribution is defined:

$$f(v,k,c) = \frac{2v(\theta)}{c^2(\theta)}\exp\left[-\left(\frac{v(\theta)}{c(\theta)}\right)^2\right] \quad (5)$$

and the cumulative distribution function is defined:

$$f(v,k,c) = 1 - \exp\left[-\left(\frac{v(\theta)}{c(\theta)}\right)^2\right] \quad (6)$$

For wind turbine sizing and energy resource analysis, the mean power densities are calculated from the expression:

$$p(v) = \frac{P_W(v)}{A} = \frac{1}{2}\rho(c(\theta))^3\Gamma\left[1+\left(\frac{3}{k(\theta)}\right)\right] \quad (7)$$

where $P_w(v)$ is the available wind power flowing through the swept area of a rotor-blade of a wind turbine, $p(v)$ is the wind power density (W/m^2), and ρ is the mean air density of each considered station point.

3.2. Rician Density Function

The Rician model has been utilized in communication theory for the fitting of scattered signals that reach a receiver in multiple paths. For the fitting of the offshore wind speed at the SW coast of Nigeria, the density function of a Rician distribution is given by the expression [35]:

$$f(v,s,\sigma) = I_o\left(\frac{vs}{\sigma^2}\right)\left(\frac{v}{\sigma^2}\right)\exp\left[-\left(\frac{v^2+s^2}{2\sigma^2}\right)\right] \quad (8)$$

where $f(v, s, \sigma)$ is a 2-parametric Rician probability density function; the scale parameter is denoted by $\sigma > 0$; the non-centrality parameter, $s \geq 0$ of the local wind speed value $v > 0$; and I_o is the zero-order modified Bessel function of the first kind.

The 2-parameter (s, σ) of the Rician distribution based on the maximum likelihood estimation are given [36]:

$$s = \frac{1}{N}\prod_{i=1}^{N} v_i \frac{I_1(z)}{I_o(z)} \quad (9)$$

$$\sigma = \sqrt{0.5\left(\frac{1}{N}\prod_{i=1}^{N} v_i^2 - s^2\right)} \quad (10)$$

where $I_1(z)$ is the first-order modified Bessel function of the first kind and z = ($v_i s/\sigma^2$). A good numerical optimization algorithm with a starting value is needed to solve Eq. (9) and cannot be solved analytically.

The mean wind power densities for the Rician distribution are calculated from the expression:

$$p(v) = \frac{P_{ric}(v)}{A} = \sum_{i=1}^{n} \frac{1}{2}\rho(v(\theta))^3 f(v,s,\sigma)_i \quad (11)$$

3.3. Performance evaluation of the statistical models

To determine how closely the Weibull, Rayleigh and Rician statistical models fit the observed wind speed at 10 m height, the performance of these models is assessed based on the following criteria: the mean square error, *MSE*; the mean error, *ME*; and the correlation coefficient, *R*.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(v_{i,pred} - v_{i,obs}\right)^2 \quad (12)$$

$$ME = \frac{1}{N}\sum_{i=1}^{N}\left(v_{i,pred} - v_{i,obs}\right) \quad (13)$$

$$R = \frac{n\sum v_{i,pred}x_{i,obs} - \left(\sum v_{i,pred}\right)\left(\sum v_{i,obs}\right)}{\sqrt{n\left(\sum v_{i,pred}^2\right) - \left(\sum v_{i,pred}\right)^2}\sqrt{n\left(\sum v_{i,obs}^2\right) - \left(\sum v_{i,obs}\right)^2}} \quad (14)$$

where $v_{i,pred}$ and $v_{i,obs}$ are the frequency distributions of the Weibull, Rayleigh or Rician wind speed; and the actual wind distribution, respectively; N denotes the number of wind data points.

4. Results and Discussion

For the satellite wind observations at 6-hourly resolution (00, 06, 12 and 18 UTC) for the period of 10-year, results derived for an annual mean wind speed at the SW/coastal region are presented in Figs. 2 and 3 and Tables 3–6. The directional flow of the seasonal mean wind speeds for summer, autumn, winter and spring are shown in Fig 4. Fig 5 presents an outlook of the wind atlas across Nigeria at a 10 m height for a 10-year period (2002-2011). The plots of different distribution functions and directions of prevailing offshore wind speed for 16 station grid points are also presented in Fig. 6. For comparisons of the land surface wind, the frequency distributions and directions of prevailing wind speeds derived from the ECMWF operational analysis as well as an integrated station hourly wind observations at 9 weather stations are presented in Figs. 7 and 8. Furthermore, an outlook of the wind speed map at a 10 m height for the southwest coastal region only is presented in Fig. 9 while the validation results of the statistical models in fitting of the satellite wind speeds are summarized in Table 7.

4.1. Regional scale wind assessment

The maps of the annual mean wind speed distributions at a 10 m height for a 10 years period (2002–2011) have been presented in Figs 2-3 while the interannual mean wind speed and power density maps have been presented in Fig 5. The prevailing wind directions in the 4 seasons (summer, autumn, winter and spring months) as captured by the wave arrows emerged from the Gulf of Guinea, Niger and Chad (Fig. 4b-d) while the dominant wind flow in winter months emerged from the Gulf of Guinea/southwest coast only (see Fig 4a). These figures also provide an appropriate description of the regional wind flow across the land in Nigeria.

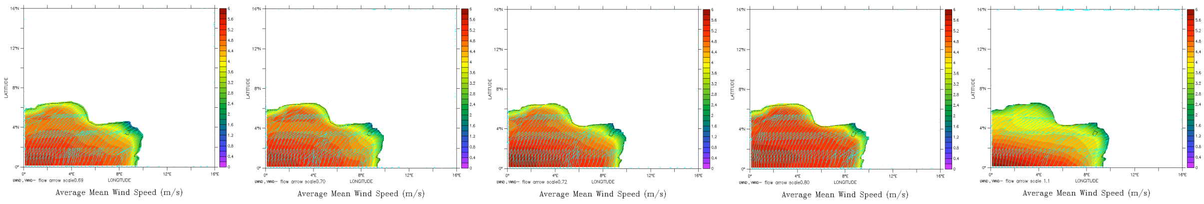

Fig. 2: Map of annual mean wind speed at South-West Coast of Nigeria in: (a) 2002, (b) 2003, (c) 2004, (d) 2005, and (e) 2006, respectively at 10 m height asl.

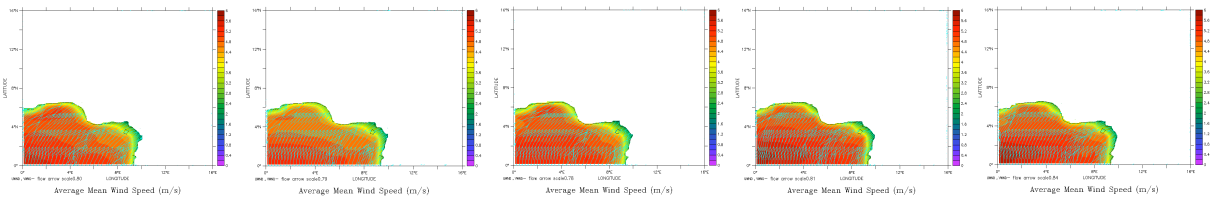

Fig. 3: Map of annual mean wind speed at South-West Coast of Nigeria in: (a) 2007, (b) 2008, (c) 2009, (d) 2010, and (e) 2011, respectively at 10 m height asl

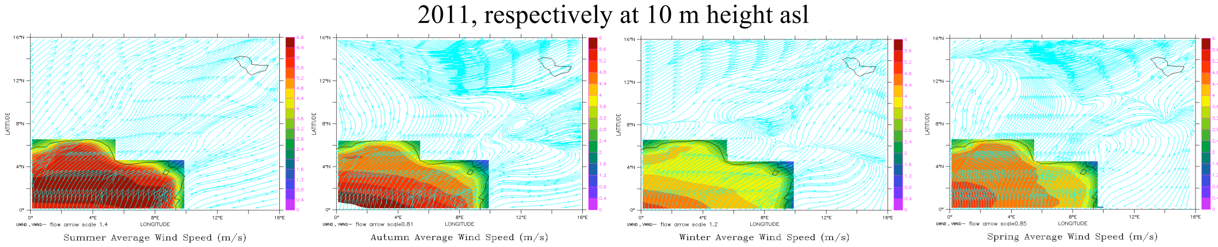

Fig. 4: Map of seasonal mean wind speed and directional flow across the land and offshore in Nigeria: (a) summer, (b) autumn, (c) winter and (d) spring, respectively at 10 m height asl

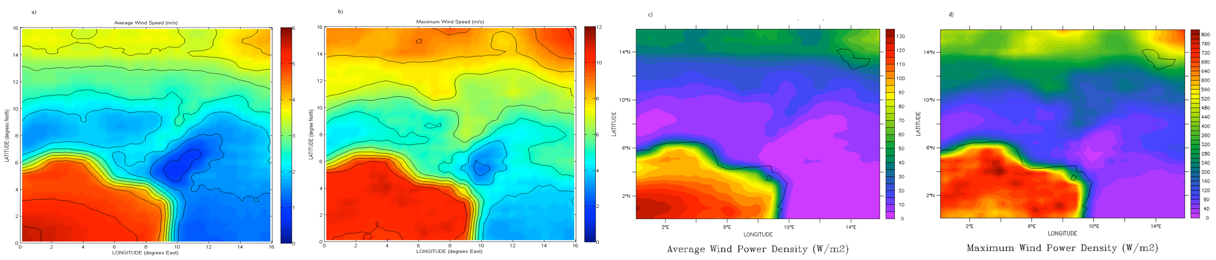

Fig. 5: Outlook of Nigerian Wind Atlas at 10 m hub height for a 10-year period (2002-2011).

Fig 6: Plot of the distribution functions and directions of prevailing offshore mean wind speed (satellite observations) at 10 m height **asl** for 16 station points.

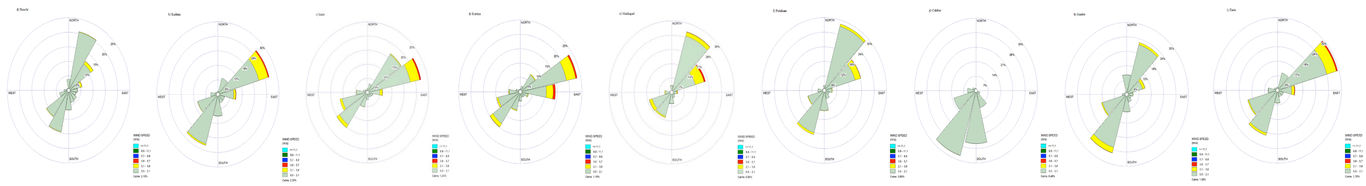

Fig. 7: Frequency distributions and direction of prevailing onshore wind speeds (from ECMWF operational analysis) at 10 m height **agl** for 9 station points.

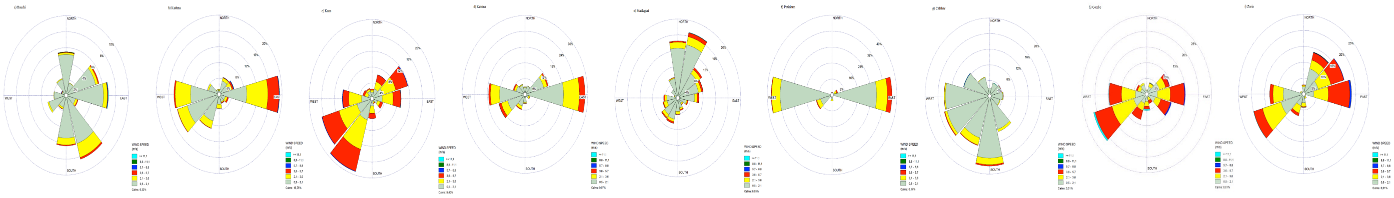

Fig. 8: Frequency distributions and directions of prevailing onshore wind (NCDC stations' surface hourly wind observations) at 10 m height **agl** for 9 station points.

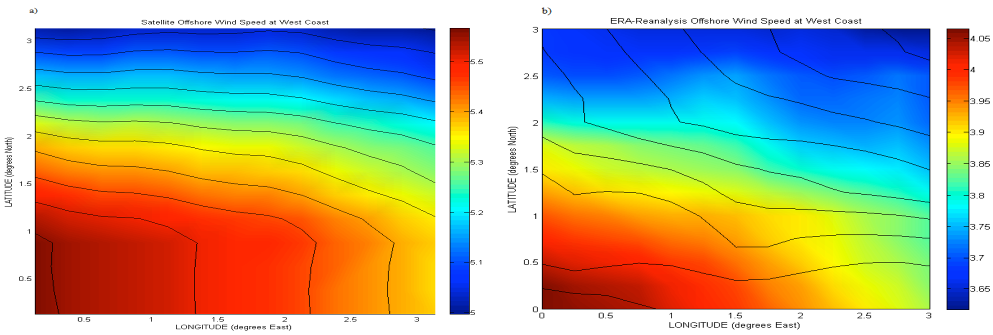

Fig. 9: Outlook of the offshsore wind speed (m/s) map at 10 m height for the coastal/South-West region of Nigeria (satellite observed and ERA-reanalysis wind speed, respectively).

Due to a difference in surface pressure systems (high and low), two predominantly wind flows were observed across Nigeria: **Southwest coast** wind flow enroutes from the Gulf of Guinea to Northern Nigeria with a cyclonic convergence in the cities of Cameroon (10-15^{o}E); **Niger and Chad** wind flow in Northern Nigeria. The convergence across Cameroon as well as small cities of Nigeria was as a result of low pressure system with the surface wind moving inwardly from high pressure areas (6^{o}E/8^{o}N and 10^{o}E/6^{o}N) while the ascending warm air diverges in the atmospheric upper level. As a result of non-availability of the wind speed observations at upper levels, it was difficult to assess the impact of the density of surface roughness elements on the surface wind speed distributions at 10 m height. In the spring months (Fig 4d), the wind flow showed a similar trend with the autumn months (Fig 4b) while in the summer and winter months, the prevailing directions differ as a result of changes in the synoptic weather system activities across the considered wind field. Furthermore, the trend of annual mean wind speed distribution shows that the surface wind was low in the southwest region and gradually increases to a relatively high speed site(s) in the northern Nigeria.

Table 3: Comparisons of the offshore monthly mean wind speeds (m/s) at 10 m height for 16 offshore stations.

Station	2002											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	4.61	4.65	4.19	4.18	5.74	6.52	6.82	6.42	6.30	5.78	5.76	4.98
B	4.56	4.58	4.17	4.15	5.73	6.53	6.85	6.49	6.28	5.74	5.73	4.98
C	4.47	4.52	4.19	4.12	5.71	6.54	6.86	6.57	6.22	5.72	5.63	4.98
D	4.42	4.46	4.19	4.14	5.65	6.55	6.86	6.63	6.16	5.69	5.54	5.01
E	4.36	4.39	4.17	4.11	5.56	6.56	6.84	6.64	6.14	5.60	5.47	4.95
F	4.23	4.35	4.13	4.09	5.44	6.58	6.83	6.63	6.11	5.49	5.44	4.88
G	4.07	4.28	4.03	4.02	5.29	6.61	6.81	6.60	6.10	5.39	5.37	4.75
H	3.95	4.20	3.94	3.96	5.18	6.64	6.81	6.57	6.12	5.30	5.30	4.65
I	3.80	4.12	3.85	3.93	5.07	6.66	6.77	6.58	6.14	5.24	5.23	4.56
J	3.62	4.07	3.79	3.92	5.01	6.70	6.77	6.60	6.19	5.20	5.17	4.46
K	4.10	4.40	4.20	4.19	5.39	6.98	7.19	6.60	6.34	5.38	4.98	4.61
L	3.98	4.38	4.24	4.20	5.34	6.96	7.22	6.71	6.33	5.39	4.98	4.60
M	3.81	4.32	4.24	4.23	5.30	6.97	7.24	6.82	6.31	5.40	4.99	4.59
N	3.79	4.23	4.23	4.25	5.28	7.00	7.26	6.90	6.28	5.37	5.01	4.60
O	3.74	4.11	4.18	4.19	5.24	7.02	7.25	6.90	6.24	5.29	4.99	4.53
P	3.67	4.05	4.13	4.12	5.14	7.04	7.23	6.85	6.18	5.21	4.96	4.46

Station	2003											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	5.04	4.52	4.20	4.82	6.08	5.96	6.17	6.54	6.51	6.23	5.39	5.17
B	5.14	4.44	4.21	4.91	6.09	5.88	6.19	6.58	6.49	6.16	5.40	5.04
C	5.18	4.36	4.23	4.97	6.07	5.78	6.15	6.58	6.43	6.06	5.38	4.94
D	5.21	4.32	4.24	5.00	6.05	5.69	6.14	6.58	6.36	5.95	5.32	4.87
E	5.18	4.29	4.20	4.98	6.02	5.61	6.17	6.61	6.31	5.85	5.19	4.78
F	5.13	4.24	4.15	4.94	5.99	5.55	6.21	6.66	6.27	5.75	5.06	4.63
G	5.10	4.19	4.11	4.86	5.96	5.53	6.23	6.68	6.21	5.69	4.89	4.42
H	5.04	4.18	4.11	4.73	5.93	5.53	6.27	6.70	6.15	5.67	4.70	4.24
I	4.29	4.15	4.09	4.60	5.90	5.54	6.27	6.69	6.08	5.64	4.52	4.07
J	4.76	4.10	4.10	4.59	5.88	5.58	6.29	6.67	6.02	5.62	4.38	3.97
K	4.74	4.53	4.20	4.79	6.16	6.15	6.45	6.56	6.29	5.73	4.84	4.66
L	4.77	4.46	4.17	4.89	6.14	6.10	6.47	6.58	6.24	5.61	4.84	4.60
M	4.77	4.40	4.15	4.98	6.12	6.05	6.47	6.62	6.19	5.48	4.76	4.53
N	4.77	4.34	4.16	5.04	6.07	6.00	6.47	6.67	6.14	5.36	4.66	4.46
O	4.77	4.26	4.15	4.97	6.01	5.94	6.45	6.70	6.09	5.27	4.51	4.33
P	4.80	4.22	4.13	4.85	5.97	5.88	6.46	6.72	6.03	5.22	4.40	4.18

Station	2004											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	4.80	4.69	4.89	5.35	5.76	6.18	6.43	6.41	6.50	6.09	5.72	5.54
B	4.77	4.61	4.90	5.40	5.70	6.21	6.47	6.42	6.53	6.01	5.66	5.43
C	4.67	4.51	4.94	5.45	5.68	6.24	6.51	6.43	6.50	5.97	5.64	5.30
D	4.54	4.46	5.00	5.46	5.69	6.29	6.55	6.44	6.47	5.95	5.63	5.15
E	4.42	4.42	5.01	5.42	5.69	6.31	6.58	6.43	6.40	5.92	5.60	4.99
F	4.32	4.39	4.95	5.40	5.70	6.37	6.62	6.41	6.33	5.91	5.56	4.87
G	4.23	4.33	4.88	5.41	5.70	6.38	6.64	6.40	6.22	5.89	5.43	4.72
H	4.20	4.24	4.87	5.45	5.71	6.36	6.65	6.38	6.15	5.87	5.31	4.52
I	4.12	4.20	4.87	5.48	5.74	6.32	6.66	6.33	6.08	5.79	5.15	4.34
J	4.02	4.18	4.91	5.53	5.79	6.31	6.69	6.32	6.06	5.71	4.95	4.18
K	4.44	4.42	4.82	5.50	6.00	6.50	6.73	6.47	6.35	5.52	5.21	5.31
L	4.41	4.35	4.81	5.55	5.99	6.49	6.77	6.50	6.35	5.48	5.19	5.23
M	4.34	4.27	4.83	5.57	5.99	6.51	6.79	6.53	6.32	5.50	5.17	5.10
N	4.27	4.18	4.86	5.60	5.99	6.51	6.82	6.55	6.29	5.53	5.16	4.98
O	4.14	4.08	4.84	5.61	5.96	6.50	6.85	6.55	6.21	5.52	5.06	4.81
P	4.03	4.00	4.77	5.59	5.93	6.49	6.86	6.54	6.11	5.54	4.98	4.68

Table 4: Comparisons of the offshores monthly mean wind speeds (m/s) at 10 m hub height (cont.)

Station	2005											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	3.87	4.40	4.63	5.82	5.83	6.32	5.93	6.07	6.37	6.15	5.88	5.56
B	3.86	4.43	4.64	5.85	5.78	6.30	5.91	6.09	6.40	6.11	5.80	5.46
C	3.84	4.45	4.60	5.86	5.74	6.33	5.89	6.13	6.41	6.02	5.73	5.34
D	3.86	4.46	4.55	5.86	5.70	6.38	5.87	6.17	6.43	5.95	5.68	5.25
E	3.82	4.43	4.50	5.81	5.66	6.39	5.86	6.17	6.44	5.84	5.64	5.14
F	3.78	4.35	4.44	5.75	5.66	6.36	5.86	6.17	6.43	5.74	5.59	5.01
G	3.73	4.27	4.34	5.69	5.67	6.35	5.68	6.18	6.41	5.64	5.53	4.88
H	3.71	4.21	4.25	5.61	5.69	6..38	5.88	6.20	6.39	5.57	5.45	4.75
I	3.69	4.16	4.17	5.52	5.67	6.44	5.92	6.23	6.35	5.47	5.36	4.60
J	3.65	4.16	4.07	5.42	5.69	6.54	6.03	6.28	6.33	5.42	5.23	4.44
K	3.74	4.26	4.56	6.01	6.43	7.02	6.12	6.18	6.29	5.72	5.32	5.12
L	3.69	4.25	4.57	5.98	6.41	7.03	6.16	6.21	6.36	5.64	5.33	5.04
M	3.68	4.25	4.55	5.92	6.40	7.04	6.18	6.24	6.40	5.56	5.34	4.96
N	3.73	4.26	4.47	5.89	6.37	7.06	6.20	6.28	6.41	5.46	5.33	4.88
O	3.73	4.25	4.34	5.84	6.37	7.05	6.19	6.30	6.39	5.35	5.31	4.76
P	3.71	4.23	4.19	5.81	6.36	7.06	6.18	6.31	6.37	5.24	5.29	4.63

Station	2006											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	4.27	4.33	4.57	3.89	5.23	6.13	5.87	6.10	6.52	6.13	5.49	5.12
B	4.31	4.31	4.57	3.93	5.09	6.04	5.92	6.11	6.52	6.15	5.39	5.14
C	4.36	4.31	4.55	3.90	4.94	6.00	6.00	6.14	6.52	6.11	5.34	5.15
D	4.43	4.26	4.51	3.91	4.84	5.97	6.06	6.20	6.49	6.09	5.32	5.14
E	3.62	4.84	4.32	4.34	5.04	6.67	6.28	6.16	6.32	6.51	5.46	5.08
F	3.59	4.88	4.30	4.26	4.90	6.65	6.27	6.19	6.27	6.48	6.35	5.04
G	3.57	4.89	4.29	4.13	4.74	6.62	6.25	6.21	6.23	6.39	5.25	4.98
H	3.53	4.83	4.27	4.01	4.60	6.61	6.26	6.24	6.13	6.29	5.18	4.90
I	3.48	4.77	4.24	3.91	4.45	6.66	6.29	6.29	6.02	6.17	5.11	4.81
J	3.46	4.71	4.24	3.85	4.30	6.72	6.31	6.33	5.94	6.05	5.05	4.77
K	4.01	4.11	4.59	3.83	4.74	6.61	6.39	6.21	6.41	5.52	4.92	4.73
L	3.46	4.95	4.36	4.45	4.76	6.99	6.61	6.28	6.21	6.25	5.21	4.49
M	3.45	4.85	4.33	4.42	4.67	7.02	6.63	6.31	6.14	6.20	5.09	4.45
N	3.43	4.80	4.32	4.39	4.59	7.06	6.64	6.34	6.10	6.14	4.99	4.42
O	3.40	4.76	4.31	4.35	4.49	7.07	6.65	6.34	6.07	6.05	4.86	4.40
P	3.42	4.73	4.28	4.27	4.37	7.07	6.63	6.34	6.04	5.95	4.78	4.38

Station	2007											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	4.95	4.55	4.41	4.11	4.99	6.34	6.08	6.49	6.50	5.80	4.98	4.66
B	4.94	4.54	4.48	4.09	5.01	6.25	6.10	6.52	6.48	5.80	4.89	4.69
C	4.87	4.54	4.48	4.06	4.97	6.22	6.14	6.55	6.45	5.77	4.83	4.69
D	4.77	4.56	4,48	4.09	4.97	6.21	6.19	6.55	6.43	5.72	4.82	4.71
E	4.52	4.19	4.47	3.90	4.75	5.93	6.09	6.23	6.45	6.05	5.31	5.11
F	4.61	4.11	4.45	3.85	4.65	5.92	6.10	6.23	6.42	6.00	5.30	5.10
G	4.62	4.07	4.44	3.75	4.49	5.93	6.08	6.20	6.38	5.89	5.30	5.02
H	4.61	4.04	4.47	3.70	4.37	5.91	6.10	6.19	6.35	5.73	5.29	4.91
I	4.58	4.02	4.49	3.63	4.28	5.86	6.12	6.19	6.29	5.59	5.23	4.76
J	4.61	4.04	4.51	3.52	4.27	5.81	6.16	6.22	6.20	5.44	5.17	4.63
K	4.72	4.49	4.50	4.12	4.59	6.96	6.56	6.85	6.45	5.71	4.41	4.34
L	4.06	4.04	4.56	3.80	4.69	6.61	6.45	6.22	6.44	5.58	4.88	4.76
M	4.08	3.97	4.56	3.79	4.62	6.58	6.51	6.25	6.43	5.58	4.86	4.79
N	4.13	3.92	4.58	3.81	4.57	6.55	6.54	6.28	6.41	5.55	4.85	4.81
O	4.18	3.86	4.56	3.78	4.49	6.54	6.55	6.28	6.36	5.45	4.86	4.81
P	4.19	3.83	4.55	3.75	4.42	6.59	6.55	6.28	6.30	5.35	4.87	4.79

Table 5: Comparisons of the offshore monthly mean wind speeds (m/s) at 10 m hub height (cont.).

Station	2009											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	5.00	4.97	4.65	5.05	5.77	6.15	6.21	6.24	6.31	6.32	5.65	5.28
B	5.00	4.95	4.64	5.01	5.73	6.14	6.22	6.25	6.34	6.27	5.60	5.14
C	4.94	4.93	4.62	4.98	5.65	6.11	6.20	6.27	6.33	6.20	5.55	5.00
D	4.87	4.92	4.62	4.98	5.57	6.09	6.19	6.29	6.32	6.15	5.51	4.93
E	4.67	4.57	4.43	4.08	4.91	6.21	6.25	6.54	6.38	5.63	4.84	4.69
F	4.60	4.61	4.38	4.05	4.81	6.21	6.29	6.56	6.31	5.58	4.92	4.65
G	4.47	4.63	4.32	3.97	4.70	6.21	6.33	6.60	6.25	5.53	4.95	4.59
H	4.34	4.64	4.30	3.88	4.59	6.22	6.39	6.64	6.20	5.48	4.99	4.54
I	4.23	4.60	4.28	3.79	4.52	6.22	6.42	6.65	6.15	5.46	4.99	4.46
J	4.18	4.54	4.28	3.76	4.49	6.26	6.44	6.66	6.13	5.46	4.99	4.38
K	4.71	4.88	4.67	4.89	5.85	6.84	6.55	6.67	6.43	6.07	5.12	4.71
L	4.76	4.51	4.56	4.10	4.60	6.91	6.61	6.91	6.45	5.70	4.38	4.38
M	4.74	4.53	4.55	4.08	4.57	6.90	6.65	6.94	6.41	5.65	4.33	4.41
N	4.71	4.52	4.55	4.08	4.55	6.89	6.70	6.96	6.36	5.61	4.32	4.42
O	4.64	4.50	4.51	4.02	4.45	6.88	6.74	6.93	6.28	5.54	4.33	4.38
P	4.52	4.52	4.44	3.93	4.35	6.87	6.78	6.90	6.20	5.47	4.38	4.32

Station	2010											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	4.81	4.94	4.40	4.42	6.15	6.14	5.86	6.43	6.14	6.55	6.28	5.59
B	4.82	4.91	4.38	4.34	6.04	6.19	5.92	6.48	6.14	6.50	6.23	5.52
C	4.72	4.78	4.31	4.26	5.97	6.22	5.96	6.52	6.09	6.39	6.11	5.50
D	4.66	4.64	4.25	4.23	5.91	6.23	5.97	6.54	6.06	6.26	5.98	5.48
E	4.76	4.86	4.57	4.94	5.49	6.07	6.19	6.30	6.29	6.15	5.48	4.81
F	4.68	4.82	4.53	4.91	5.44	6.05	6.21	6.32	6.26	6.16	5.47	4.76
G	4.56	4.77	4.43	4.85	5.43	6.03	6.24	6.33	6.18	6.12	5.43	4.70
H	4.48	4.76	4.35	4.82	5.43	6.01	6.28	6.33	6.12	6.08	5.44	4.69
I	4.33	4.72	4.23	4.76	5.43	5.94	6.33	6.35	6.07	5.97	5.42	4.60
J	4.23	4.66	4.15	4.75	5.41	5.89	6.40	6.39	6.07	5.88	5.45	4.58
K	4.43	4.92	4.43	4.35	6.41	6.96	6.69	6.58	6.24	6.10	5.73	4.86
L	4.76	4.91	4.65	4.90	5.80	6.78	6.56	6.64	6.44	5.97	5.10	4.64
M	4.73	4.93	4.59	4.90	5.72	6.72	6.55	6.66	6.42	5.87	5.06	4.55
N	4.69	4.93	4.57	4.96	5.64	6.66	6.57	6.69	6.42	5.82	5.03	4.48
O	4.67	4.88	4.52	4.96	5.56	6.58	6.56	6.73	6.41	5.82	5.00	4.36
P	4.62	4.85	4.44	4.94	5.53	6.51	6.55	6.77	6.39	5.84	5.03	4.30

Station	2011											
IDs	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
A	4.81	4.94	4.40	4.42	6.15	6.14	5.86	6.43	6.14	6.55	6.28	5.58
B	4.82	4.91	4.38	4.34	6.04	6.19	5.92	6.48	6.14	6.50	6.23	5.52
C	4.72	4.78	4.31	4.26	5.97	6.22	5.96	6.52	6.09	6.39	6.11	5.50
D	4.66	4.64	4.25	4.23	5.91	6.23	5.97	6.54	6.06	6.26	5.98	5.48
E	4.57	4.49	4.17	4.22	5.79	6.22	5.93	6.53	6.02	6.11	5.81	5.42
F	4.50	4.43	4.15	4.23	5.68	6.21	5.88	6.53	6.03	5.98	5.70	5.38
G	4.38	4.30	4.11	4.16	5.55	6.20	5.88	6.54	6.04	5.84	5.60	5.31
H	4.30	4.28	40.8	4.12	5.44	6.19	5.94	6.56	6.05	5.73	5.52	5.25
I	4.16	4.09	4.02	4.08	5.30	6.20	6.04	6.56	5.99	5.63	5.44	5.16
J	4.09	4.00	4.00	4.05	5.17	6.26	6.13	6.56	5.92	5.53	5.42	5.07
K	4.43	4.92	4.43	4.35	6.41	6.96	6.69	6.58	6.24	6.10	5.73	4.86
L	4.40	4.86	4.43	4.31	6.32	6.96	6.73	6.63	6.24	6.00	5.66	4.84
M	4.30	4.72	4.37	4.23	6.23	6.92	6.75	6.69	6.18	5.87	5.53	4.87
N	4.25	4.67	4.32	4.24	6.14	6.88	6.78	6.75	6.13	5.75	5.40	4.93
O	4.15	4.56	4.27	4.25	6.05	6.87	6.78	6.76	6.09	5.63	5.25	4.94
P	4.10	4.49	4.24	4.27	5.99	6.86	6.77	6.77	6.07	5.52	5.13	4.96

Table 6: Comparisons of the annual minimum (min), mean and maximum (max) offshore wind speeds (m/s) at 10 m hub height for 16 station points (A-P).

Station	2002			2003			2004			2005		
IDs	min	mean	max	min	Mean	max	Min	mean	max	Min	mean	max
A	0.27	5.50	10.72	0.70	5.56	10.55	0.52	5.70	9.86	0.37	5.57	9.76
B	0.03	5.49	10.31	0.67	5.55	10.29	0.66	5.68	9.91	0.38	5.55	9.66
C	0.16	5.47	10.11	0.32	5.52	10.15	0.42	5.66	9.51	0.33	5.53	9.57
D	0.33	5.45	10.06	0.34	5.49	10.13	0.36	5.63	9.49	0.51	5.51	9.69
E	0.41	5.40	10.08	0.08	5.44	10.09	0.33	5.60	10.37	0.66	5.47	9.31
F	0.29	5.36	10.27	0.29	5.39	10.12	0.38	5.57	10.96	0.40	5.43	9.29
G	0.26	5.28	10.48	0.11	5.33	10.01	0.38	5.52	9.93	0.29	5.38	9.29
H	0.26	5.22	10.50	0.43	5.28	9.86	0.15	5.48	9.98	0.39	5.34	9.50
I	0.15	5.17	10.45	0.27	5.21	9.64	0.53	5.43	10.11	0.21	5.30	9.59
J	0.19	5.13	10.32	0.19	5.17	10.01	0.26	5.39	9.79	0.29	5.27	9.52
K	0.07	5.37	11.34	0.43	5.43	10.49	0.38	5.61	9.74	0.13	5.57	9.95
L	0.31	5.37	11.00	0.41	5.41	10.42	0.37	5.60	10.06	0.30	5.56	9.91
M	0.29	5.36	10.10	0.54	5.38	10.53	0.43	5.58	10.33	0.27	5.54	10.11
N	0.18	5.35	10.21	0.06	5.35	10.33	0.16	5.56	10.48	0.17	5.53	10.14
O	0.34	5.31	10.28	0.17	5.30	9.87	0.39	5.51	10.51	0.15	5.49	9.91
P	0.22	5.26	10.13	0.24	5.25	9.49	0.23	5.46	10.45	0.23	5.45	9.87

Station	2006			2007			2008		
IDs	min	mean	max	min	mean	Max	Min	Mean	max
A	0.46	5.58	10.22	0.45	5.53	10.74	0.59	5.31	10.39
B	0.43	5.56	10.04	0.52	5.50	11.04	0.87	5.29	10.01
C	0.30	5.54	9.83	0.54	5.46	11.11	0.50	5.28	9.95
D	0.38	5.52	9.84	0.52	5.43	11.06	0.49	5.27	10.18
E	0.37	5.47	9.96	0.49	5.39	10.70	0.35	5.26	10.28
F	0.34	5.43	10.16	0.43	5.35	11.01	0.29	5.23	10.13
G	0.26	5.33	9.92	0.43	5.30	10.83	0.48	5.19	9.65
H	0.30	5.37	9.96	0.77	5.24	10.49	0.33	5.18	9.30
I	0.29	5.27	9.94	0.70	5.18	10.18	0.55	5.09	9.27
J	0.23	5.24	9.91	0.49	5.14	10.36	0.26	5.05	9.53
K	0.25	5.49	10.38	0.27	5.37	10.61	0.22	5.18	10.32
L	0.34	5.48	10.34	0.31	5.33	10.70	0.19	5.18	10.21
M	0.38	5.46	10.26	0.09	5.30	10.54	0.28	5.17	9.93
N	0.14	544	10.29	0.41	5.27	10.96	0.50	5.17	9.78
O	0.26	5.40	10.14	0.24	5.23	8.24	0.77	5.15	9.81
P	0.23	5.35	9.98	0.25	5.19	10.79	0.60	5.13	9.46

Station	2009			2010			2011		
IDs	Min	mean	Max	min	mean	max	min	mean	Max
A	0.04	5.33	9.80	0.18	5.64	9.50	0.13	5.65	10.16
B	0.35	5.32	9.83	0.28	5.61	9.45	0.47	5.63	10.14
C	0.11	5.30	9.72	0.30	5.57	9.75	0.41	5.57	9.89
D	0.17	5.30	9.47	0.63	5.54	9.71	0.35	5.52	9.68
E	0.10	5.27	10.07	0.33	5.50	9.46	0.65	5.45	9.62
F	0.08	5.25	10.14	0.51	5.47	9.54	0.46	5.40	9.48
G	0.35	5.22	9.60	0.29	5.43	9.56	0.37	5.33	9.55
H	0.23	5.19	10.03	0.19	5.40	9.73	0.21	5.29	10.18
I	0.25	5.15	10.08	0.27	5.35	9.96	0.4	5.23	9.45
J	0.12	5.13	10.01	0.54	5.32	10.23	0.61	5.19	10.34
K	0.26	5.32	9.51	0.53	5.62	10.13	0.66	5.64	11.43
L	0.23	5.33	9.71	0.33	5.60	9.70	0.35	5.62	11.29
M	0.12	5.32	9.88	0.30	5.56	9.64	0.17	5.56	11.8
N	0.13	5.31	10.17	0.47	5.54	9.69	0.08	5.53	10.81
O	0.27	5.27	10.26	0.50	5.50	9.38	0.09	5.47	10.45
P	0.39	5.23	10.30	0.46	5.48	9.32	0.06	5.44	10.18

Table 7. Validation results of the statistical models in fitting of the satellite wind speed at 10 m height asl for 16 offshore stations (A-P); where MSE = $1x10^{-5}$, Weib, Ric and Rayl are the Weibull, Rician and Rayleigh distributions, respectively.

pdfs	A		B		C		D		E		F		G		H	
	MSE	R	MSE	R	MSE	R	MSE	R	MSE	R	MSE	R	MSE	R	R	MSE
Weib	7.514	0.993	11.53	0.990	6.129	0.994	7.514	0.995	4.531	0.995	3.821	0.996	3.080	0.997	2.392	0.998
Ric	0.161	0.999	0.751	0.999	0.190	0.999	0.163	0.999	0.239	0.999	0.271	0.999	0.322	0.999	0.382	0.999
Rayl	892.5	0.491	888.4	0.517	823.7	0.507	892.5	0.491	818.2	0.356	795.0	0.321	775.0	0.296	743.3	0.273

pdfs	I		J		K		L		M		N		O		P	
	MSE	R	MSE	R	MSE	R	MSE	R	MSE	R	MSE	R	MSE	R	MSE	R
Weib	1.974	0.998	1.770	0.998	2.636	0.997	2.404	0.998	2.269	0.998	2.181	0.998	2.777	0.998	1.929	0.998
Ric	0.450	0.999	0.516	0.999	0.336	0.999	0.365	0.999	0.394	0.999	0.429	0.999	2.318	0.998	0.552	0.999
Rayl	717.8	0.257	687.5	0.238	564.6	0.557	542.4	0.579	523.5	0.577	564.0	0.4023	612.4	0.273	577.1	0.274

For assessment of an ideal wind site for energy conversion across the nation, the minimum, mean and maximum wind speeds from the satellite observed wind at 10 m height asl have been estimated (Table 6). A hourly mesoscale modeling or/and station's measured winds (if available) would produce similar energy trend with the satellite observed winds at 6-hourly resolution (Fig 5), exception to the magnitude of wind speed/density distributions at the offshore. On a regional scale, the offshore wind in SW coast has the highest energy resource for power conversion, followed by the north-east and -west regions while the southwest and southeast regions have the lowest resource unsuitable for stand-alone energy application. That is, higher winds would be observed over the land in North region than in the south region of Nigeria with the highest wind speeds achievable at the coastal region. Due to seasonal lag at the temperate and polar regions linked to changes in the weather system activities or solar energy variations across different grid points on the earth surface, the seasonal wind energy fluxes from the SW coast to the onshore have been determined. Nigeria being suitated in Northern Hemisphere has a higher mean wind speed value at 6.54 m/s in summer (JJA) compared to the winter month (DJF) with a mean value recorded at 4.40 m/s. Meanwhile, the autumn months also experience high wind speed with mean value estimated at 5.52 m/s (SON) compared to the spring months (MAM) with a mean value of 4.84 m/s (Fig 4). Being close to the equator, Nigeria experiences a constant solar radiation with high wind climate prevailence in JJA while the southern hemisphere recorded a low wind climate for similar months (JJA).

Using high resolution satellite observations, the prevailing directions of wind flow at different grid points across the country are analyzed. Ajayi et al [27] analyzed the dominant wind directions at Kano synoptic station to be Northeasterly and Southwesterly. Their predictions agree with the studied findings obtained for similar synoptic station using ECMWF operational analysis winds and integrated station hourly observations sourced from the archive of NCDC (see Fig 7c and 8c). Comparing the findings in literature (Fig. 7 a and b) [27] with the studied results (Fig 4a and c), the southwesterly (summer, JJA) and northeasterly (winter, DJF) winds were dominant at Kano station.

In energy resource study, regional wind speed and direction maps are very essential for assessing high resolution wind energy resource across both flat and heterogeneous surface terrains. Thus, the mean values of the annual wind speed and power density at 10 and 50 m hub heights have been adopted in literature as benchmark for wind power classification at a given surface field. From an outlook of the wind speed map across Nigeria (Fig 5), steady offshore wind speed (k > 2) at the SW coast was recorded with annual mean and maximum wind speed values at 5.32 and 10.32 m/s, respectively. Also, the mean and maximum wind power densities were estimated at 116 and 679 W/m^2, respectively, for 6-hourlyobservations. Although, a 6-hourly resolution observed wind speed was utilized for this study with a fairly monthly mean wind speed values (see Fig 9a and Tables 3-5), results indicate that the considered offshore region possesses higher wind resource (class of 2-7) based on classification of the wind speed and power density at a 10 m height above the surface.

Finally, an outlook of the coastal/offshore wind speed map derived from the satellite observations and reanalysis winds is compared (see Fig. 9a-b). Due to unresolved smaller-scale features in the ECMWF reanalysis wind field, the reanalysis wind didn't correlate nor connect with the satellite observed wind across the coast. The wind speed distributions derived from the ERA reanalysis wind speed were misrepresented at different points across the coast when compared to satellite observations. With the reanalysis wind (Fig 9b), the offshore wind speed distribution was not uniform with satellite wind speed for the same domain (Fig 9a). Hence, there is need for the postprocessing/cleansing of the ERA reanalysis wind for an accurate representation of the surface wind speed before application in resource assessment across the land and ocean of Nigeria.

4.2. Local scale wind assessment

The mean values of the monthly wind speeds at 10 m height for 16 offshore stations in the coast have been summarized (Tables 3 –5), and range from 3.40 – 7.26 m/s for a 10-year period. Although, the changes in the atmospheric circulation patterns were mainly responsible for the surface monthly wind speed variations, however, decreasing trend of the near-surface annual mean wind speed for period of 10 years was not pronounced at different grid stations of the coast. Across the considered 16 stations, there were continuous decrease and increase (non-monotonic trend) of the monthly wind speeds from the month of January to December.

The plots of different pdfs in fitting of the mean wind speeds and the prevailing wind directions at 10 m height asl for the 16 offshore grid stations have been presented in Fig 6a-b. It could be observed that the Rician and Weibull pdfs were better tools in fitting of the offshore wind speeds than the Rayleigh model (Fig 6a). On a local-scale wind assessment, the two dominant directions of the wind flow (Fig. 6b) across the 16 grid stations were the: southerly (S) and southwesterly (SW), and these agree with the seasonal wind flow. The predominant directions of the seasonal wind flow were the: southerly and southwesterly (see Fig. 6c-f). Invariably, the prevailing wind climate at the southwest coast of Nigeria is basically driven by Gulf of Guinea synoptic weather system.

Further to this, the onshore wind speed distributions across nine station points were analyzed with ECMWF operational analysis wind and available hourly measured wind sourced from the NCDC. Figs. 7 and 8 show the directions of the prevailing wind speed at a 10 m height in Nigeria. Although, the magnitude of monthly wind speed recorded in existing literature (measured wind) was higher than the wind studied findings with the ECMWF analysis, however, the ECMWF wind was useful in determining the wind circulation across the land in Nigeria. Out of the nine stations identified as promising wind speed turbine sites, the operational analysis wind didn't accurately captured the directional wind flow except for few station points: Kano (Figs. 7c and 8c), Maiduguri (Figs. e of 7 and 8), Calabar (Figs. g of 7 and 8) and Zaria (Figs. i of 7 and 8). The dominant flow at Kano station reveals that the prevailing wind resource emerged from the SW and NE directions. For Maiduguri station, the wind flow from Niger and Chad enroute to Nigeria in the north (N) and NE directions. For Zaria station, the directions of wind flow at 10 m height agl are the easterly (E), NE and the SW. Calaber station benefits mainly from the wind flow emerging from the SW coast only. Also, the wind directions at this station are S and SW.

The frequency distributions of the local wind speeds for the above synoptic stations were compared with other findings in the literature. Fig. 8 revealed that Kano, Gombe and Zaria have tendency for higher wind energy conversion compared to other considered stations. Ajayi et al [27] utilized a 21 years (1987–2007) measured wind and predicted the monthly mean wind speed values to be 6.6 – 9.5 m/s for Kano station. Based on the regional wind circulation, this station is situated in a high wind speed site in the NW region, benefiting from a bi-directional wind flow in the SW and NE directions. Fagbenle et al in their studied findings recorded monthly mean wind speed variations ranging from 4.35 – 6.33 m/s for a period of 21 years at Maiduguri station. For Potiskum station, the monthly mean wind speed variation ranges from 3.90–5.85 m/s [24]. From a geographical description, both stations were situated in the NE region (Fig 1b) sharing similar wind directions (see Fig. 7e and f) and subject to the wind conditions originated from Niger and Chad. Their findings when compared with the present studied results correlate based on the directions of wind flow in the NE and NW. Okeniyi et al in their studied findings at selected stations in 3 different geopolitical zones recorded annual mean wind speed variations ranging from 6.50 – 10.94 m/s for Katsina (NW); 3.30 – 4.71 m/s for Warri (SW); 4.03 – 4.96 m/s for Calabar station (SE) [22]. From Fig 1b, Katsina station was located in high wind speed site while Warri and Calaber were low wind sites based on the wind circulation in Nigeria. Ohunakin analyzed the monthly and seasonal wind speed variations in the NE region based on a 37 years period (1971–2007) measurements at 10 m height for Bauchi, Nguru, Maiduguri, Yola and Potiskum [37]. The studied findings presented by this author suggests Bauchi and Maiduguri to be higher wind speed sites, followed by Potiskum while Nguru and Yola stations both have low wind potential suitable for battery charging and water pumping applications only. For this studied findings, the distribution of the near-surface wind speeds for Maiduguri, Potiskum and Yola were consistent with those recorded for these stations except for Nguru. The wind flow study using the ECMWF operational wind (2002-2011) across Nigeria as well as the isovents annual mean wind speed distribution map (derived from Nigerian measured winds from 1968-1983) suggest Nguru to be a high wind speed site [39]. Disparity in the reported wind speed density at Nguru may be linked to the quality of wind data sourced from this station, the period of years in which the wind data was utilized, heights in which the measured wind over time was collected, changes in the wind speed pattern across the country as a result of deforestation or global warming, among others [38]. From the studied findings reported for different synoptic stations across Nigeria; Sokoto, Nguru, Kano, Potiskum, Maiduguri, Jos, Zaria and Bauchi were high wind speed sites based on the wind speed ditributions assessed from Gulf of Guinea, Niger and Chad using the ECMWF Operational analysis winds.

4.3. Connectivity of different pdfs

Table 7 summarized the validation results of the Rician, Rayleigh and Weibull models in fitting of the coastal wind speeds at 10 m height. It can be seen from the table that the Rician and Weibull pdfs accurately fitted the offshore wind for all station points at 10 m height. Correlation coefficient values were estimated at 0.99 and exception to the Rayleigh model that performs poorly with offshore wind. Thus, Rician and Weibull pdfs are suitable for energy studies in describing the wind speed variations and analyzing the offshore wind speed distributions at 10 m height asl.

5. Conclusion

The offshore wind speed distributions at 10 m height asl in 16 selected virtual stations of the southwest coastal region of Nigeria have been assessed. In addition, the offshore map of the wind speed distribution (satellite and ERA-reanalysis wind speed) as well as the prevailing wind directions at 10 m height have been analyzed. Based on a 10-year satellite wind speed records at 10 m height, the selected stations fall under class 2–7 for the wind power site. From the studied findings, results also indicated higher wind speed potential at the south -west coastal region than those of the onshore in the north region of Nigeria. The interannual mean wind speed was recorded at 5.32 m/s with the maximum wind power density between the values of 586 and 740 W/m^2. Meanwhile, the summer, autumn, winter and spring mean wind speed values at 6.54, 5.52, 4.40 and 4.84 m/s, respectively, were also recorded. This indicates that that summer months (JJA) is an ideal season to explore the enormous wind energy resource at the coast.

The suitability of the Rician and Weibull pdfs have been assessed and was shown to be suitable models in statistical analysis of the offshore wind speed distribution at a 10 m height.

Fıgures 2–5 and 9 have provided possible answers to the frequently asked questions regarding the onshore/offshore wind speed potential at 10 m height for energy generation in Nigeria. Although, the wind energy resource is non-evenly distributed across the nation, however, Nigeria benefits from high wind conditions that emerged from the Gulf of Guinea, Niger and Chad (high pressure regions). Furthermore, an outlook of the developed wind speed map showed that the wind energy potentials at the offshore and the onshore in the northern region for grid-connected electrical application are enormous. An hourly observed winds (if available) at the considered grid stations would be more appropriate for higher wind speed and energy density assessment than using a 6-hourly wind speed at 10 m height asl.

Finally, the studied findings reported in this article is based solely on the preliminary studies of the offshore wind speed distributions derived from the satellite winds retrieval (RSS) at 6-hourly resolution for a 10-year period (2002-2011). At different hub heights over a longer period, it is also necessary to thoroughly carry out a detailed wind measurements or the simulations of the local wind conditions (such as: the air temperature, atmopheric pressure, wind speed and direction, gust wind speed, among others) using the mesoscale model. Wıth a detailed wind measurements at strategic locations, the reliability of satellite observed winds at 10 m height over the considered coastal region can be assessed for a more accurate wind speed mapping.

Appendix A./Supplimentary data

Supplementary data related to this article can be found at:

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