Journal of Cleaner Production

In-Situ Based Observation and Reanalysis-derived Wind Data for Offshore Wind Energy Potential in the Gulf of Guinea

--Manuscript Draft--

Manuscript Number:	
Article Type:	Original article
Keywords:	ERA; buoy-station observation; Weibull distribution function; Wind energy; Gulf of Guinea
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Abstract

This study investigates offshore wind energy resources over five synoptic stations along the offshore of Nigeria, located within Guinea Gulf of Guinea (GoG). It utilizes buoy-station observations of wind from 1979 to 2015 to validate the use of high-resolution RegCM4 Regional Climate Model CORDEX-CORE simulations driven by ERA-Interim (ERA). The Weibull distribution function was adopted to estimate parameters for the evaluation of offshore wind energy potential based on characteristics intrinsic to energy conversion in the study area. The Mann–Kendal test was used to assess the statistical significance of trends and inter-annual variability. A series of standardized criteria such as wind power density (WPD), coefficient of variation (CV), monthly variability index (MVI), accessibility, extreme wind speed, and distance to the coast were adopted to determine the most suitable locations for offshore wind energy exploitation over the study area. The results revealed that the ERA simulations has appropriate spatial and temporal resolution and fits the field measurements of sea surface wind speed fairly well. Low and insignificant (at $p = 0.05$) negative model bias, MB ($-0.07 \leq$ MB ≤ -0.28 ms^{-1}) and percentage bias, PMB ($-2.12 \leq$ PMB $\leq -7.06\%$) were obtained in 80% of the stations. The wind power potential in the GoG varied with the distance from the coast. Agbami station showed the best potential for wind power resources with daily mean and annual total WPD of 2.50 ± 0.50 kW m^{-2} and 1.02 ± 0.17 MWm^{-2}, respectively. There were indications of abundant wind power availability and generation at the selected sites, going by the low variability and intermittency obtained in terms of trends, range, CV, MVI and extreme wind speed episodes.

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1. Introduction

Rapid and continuous exploitation of conventional energy resources has caused a significant increase in the emitted carbon dioxide in the atmosphere, which worsens global warming trends (Aboobacker et al., 2021). This has become a topical matter in recent times, and calls for serious concern, especially in Africa, where oil and gas (fossil fuels) are largely relied upon for power production (Sawadogo et al., 2020). Africa's electric energy matrix comprises mostly energy from hydroelectric power plants, and approximately 60.8% (Sant'Anna de Sousa Gomes et al, 2019). This large participation in the overall energy mix presents some vulnerability in periods of drought and other environmental disasters.

Literature has shown that using clean and renewable energy resources is paramount for sustainable development in any part of the world (e.g., Shu et al., 2015; Sawadogo et al., 2020; Aboobacker et al., 2021; Jurasz et al., 2021). Wind energy is one of these renewable energy resources which has not been maximally exploited in African countries and many others. This is partly due to the high cost of installation and maintenance, and the fact that little is known about wind characteristics and the wind energy potential of the region.

The basic starting point for harvesting offshore wind energy in any region is the abundance of wind resources. A major question now is how ocean resources can contribute to renewable energy in Africa, thereby bringing opportunities to millions of Africans, and also reducing carbon emissions. It has been revealed that continental Africa has vast offshore renewable energy resources and is also endowed with onshore renewable energies, which are more feasible to exploit today (ANRC-AfDBG, 2021). More specifically, a few western African offshore locations have moderate (about 8 m/s such as Senegal and Benin) to high (>= 10 m/s such as Cape Verde) annual wind speed at 100 m compared to other parts of the sub-region (Elsner, 2019). Hence, countries in West Africa with existing offshore industries (oil and gas drilling industries), may possess or can develop, a strong offshore capacity that will enable them to use offshore renewables at scale, especially offshore wind power development (ANRC-AfDBG, 2021). Therefore, future advances in wind power technology could provide abundant energy for West African countries through the vast offshore resources, by utilizing their experiences from oil and gas drilling companies. Consequently, future investment in offshore wind power development could also have the potential to reduce costs associated with offshore wind energy generation, especially in West Africa. At the moment, the growth of offshore technology is only noticeable in countries in Europe, Asia, and America. It is worth noting that the global efforts and commitments to reduce the emissions of greenhouse gases will further lead to a promising future for this technology in many offshore areas of the world (Esteban et al., 2011; Nie and Li, 2018; Soukissian et al., 2021; Tian et al., 2021). However, to date, the abundant offshore wind energy on the West African coast has not been investigated. This is majorly due to a lack of long-term offshore wind observation data, and insufficient funds, inadequate modern technology, and a lack of robust quantitative analysis that evaluates the offshore wind energy potential of the region; hence, offshore wind resources of the region have not been harnessed. A few studies previously conducted at the inland coastline of

Lagos, Nigeria, have shown that offshore wind projects could be viable at this location (Olaofe, 2017; Elsner, 2019). Comprehensive works are thus required to assess the vast offshore wind energy potential on the coast of West Africa.

Therefore, the aim of this study is to assess the spatial and temporal patterns of wind power resources of offshore sites in Nigeria, located within Guinea Gulf of Guinea (GoG). The specific objectives are (a) to utilize buoy-station observations of wind speed to validate the use of high-resolution RegCM4 Regional Climate Model CORDEX-CORE simulations driven by ERA-Interim for the assessment of wind energy potentials of some selected synoptic offshore locations in the GoG, and (b) to adopt a series of standardized criteria as fully described in *Section 2.2* to determine the suitable locations for offshore wind energy exploitations over the study area. This present study is a useful platform from which more targeted policies and project plans on offshore wind energy generation and utilization, can be well developed in West Africa.

2. Methodology

2.1 Study area

The study area considers five offshore synoptic stations in the GoG (Fig. 1). The offshore locations include Forcados (5.17^o N, 5.18^o E; on the coast), Bonny (4.40^o N, 7.14^o E; on the coast), Sea Eagle (4.80^o N, 5.31^o E; on shallow water, 49 nautical miles off the coast of Warri, Nigeria), Bonga (4.56^o N, 4.62^o E; on deep water, 72 nautical miles off the coast of Warri, Nigeria), and Agbami (3.46^o N, 5.56^o E; on deep water, 131 nautical miles off the coast of Warri, Nigeria). The GoG could be described as a maritime area located within the West and Central African coastlines and the surrounding territorial waters of the Atlantic Ocean to the east of the Greenwich meridian line. The climate of the GoG, like any other region in West Africa, is dominated by the West African Monsoon (WAM), which is characterized by fluctuations of tropical maritime air mass and tropical continental air mass. The region is highly humid with an annual rainfall of more than 2,000 mm year^{-1} (Grist and Nicholson, 2001; Abiodun et al., 2012). Rainfall commences in the inland coastline of the GoG around February/March and spreads northwards from the continental coastline through the middle zone between April and May, to eventually getting to the northernmost part of the inland region between May and June (Abiodun et al., 2012). The areas within this region have low-temperature variability, typically from 21°C to 30°C with a two-peaked rainy season in June and September (ANRC-AfDBG, 2021). The selected stations are scattered over the shallow and deep sea along the coastline of Nigeria, West Africa.

2.2 Methods

Daily Buoy-station measurements of surface wind speed at 10 m for the five selected offshore synoptic stations during the 1979-2015 Special Observation Period (SOP) were obtained and analyzed. A detailed description of the measurements at the synoptic stations has been documented in Ohunakin et al. (2022). We also analyzed daily sea surface wind speed of high-resolution RegCM4 Regional Climate Model CORDEX-CORE simulations driven by ERA-Interim (shortnamed ERA in this paper) over the entire African domain (AFR-22), with a spatial resolution of 0.22° × 0.22° (≈ 25 km × 25 km) for the SOP. Within the CORDEX framework, RegCM version 4.7 from ICTP (Abdus Salam International Centre for Theoretical Physics), was deployed to downscale the ERA-Interim re-analysis (Remedio et al., 2019; Teichmann et al., 2020). The grids of all the AFR-22 simulations have 25 km grid-spacing with 41 vertical sigma levels (Giorgi et al., 2012). The oceanic boundary conditions for the simulations were taken from the driven GCM with the choice of Shallow convection scheme and MM5 Non-Hydrostatic core without a large-scale option (Giorgi et al., 2012; Adeniyi 2017; Adeniyi, 2019). The Lake Coupling described in Hostetler et al. (1993) with modification after Bennington et al. (2014) was adopted. Detailed descriptions of the initial and lateral boundary conditions and various improved schemes adopted in the CORDEX models are well documented in the literature (Giorgi et al., 2012; Adeniyi, 2019).

The sea surface wind speed from ERA was thereafter validated with the synoptic observations. Performance evaluation of the ERA model in replicating the observed sea surface wind speed over the study sites was done using appropriate statistical indices such as root-mean-square-error (RMSE), mean bias (MB), percentage mean bias (PMB), correlation coefficients (r), and Nash-Sutcliff Efficiency (NSE) as expressed in Equations (1) to (5) respectively (Moriasi et al., 2007; Kronenberg et al., 2013; Peng et al., 2019; Matthew, 2022).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left((SIM_t - OBS_t)\right)^2}{N}} \quad (1)$$

$$MB = \frac{1}{N}\sum_{t=1}^{N}(SIM_t - OBS_t) \quad (2)$$

$$PMB = \frac{\frac{1}{N}\sum_{t=1}^{N}(SIM_t - OBS_t)}{\frac{1}{N}\sum_{t=1}^{N}(OBS_t)} \times 100\% \quad (3)$$

$$r = \frac{\sum_{i=1}^{N}(SIM_t - \overline{SIM_t})(OBS_t - \overline{H}_{obs_t})}{\sqrt{\sum_{i=1}^{N}(SIM_t - \overline{SIM_t})^2 \sum_{i=1}^{N}(OBS_t - \overline{OBS_t})^2}} \quad (4)$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(OBS_t - SIM_t)^2}{\sum_{i=1}^{N}(OBS_t - \overline{OBS_t})^2} \quad (5)$$

where t is the time scale, OBS is the synoptic observation, SIM is the ERA model simulation, and N is the total number of grid cells. The significance or otherwise of the RMSE, MB and PMB were investigated using t-test statistics at $p \leq 0.05$ significant level.

We extrapolated the sea surface wind speeds (at 10 m height) of all grid points to a turbine hub height of 100 m using the Power law method based on the Weibull probability density function (Ohunakin, 2011; Ohunakin et al., 2011; Ohunakin and Akinnawonu, 2012).

From the Weibull probability density function, a time series of wind power density, $P_{D,}$ (in Wm^{-2}) was computed as:

$$P_D = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{6}$$

where ρ is the density of the atmospheric air.

We also carried out a correction of wind speed for air density and humidity, as done in Karnauskas et al. (2018). A series of standardized criteria (such as wind power density, coefficient of variation, monthly variability index, accessibility, extreme wind speed, distance to the coast, and water depth were adopted, as done in Wen et al. (2021), to determine suitable locations for offshore wind energy exploitations over the shallow and deep sea, in the GoG.

The coefficient of variation (CV) is a negative indicator and defined as the ratio of the standard deviation to the mean value of wind power density. It describes the resource volatility on a monthly scale. A low value of CV is an indication of high stability of wind energy. On the other hand, the monthly variability index (MVI), is the ratio of the difference between the highest and lowest monthly means of wind power density to its annual average value. It is commonly used to assess the intra-annual variation of the wind energy resources. Another crucial consideration for offshore structures is the device survivability in extreme conditions (Wen et al., 2021). It has been established that increasing frequency and intensity of extreme climate events could have significant impacts on offshore wind farms (Chou et al., 2019). Hence, good accessibility to offshore wind farm facilities (the percentage of time the ocean parameters such as wave height, wind speed, and peak period are equal to or less than the certain thresholds) is very crucial for operation and maintenance of the farm (Gallagher et al., 2016). Therefore, in this present study, the thresholds of 13 s for the peak period, 2 m for significant wave height, and 16 ms^{-1} for wind speed were adopted as used in Gallagher et al. (2016) and Wen et al. (2021).

Similarly, short water depth can reduce the cost of transporting power to the land, and as such, offshore locations less than 50 km to the coast as recommended in the literature (e.g., Chen et al., 2017; Emeksiz and Demirci, 2019; Wen et al., 2021), were considered. Furthermore, the Mann–Kendal test was used to assess the statistical significance of trends and inter-annual variability of wind energy.

3. Results and Discussion

3.1 Comparisons between buoy-station observations and ERA simulations of wind speed

Figure 2 depicts the observed (OBS) and simulated (ERA) monthly means of the sea surface wind speed at the five selected offshore synoptic stations along the coastline of Nigeria, located within the GoG. The annual cycle of ERA simulations of the wind speed show very similar pattern with the OBS at the five offshore locations. Although ERA simulations were found to be slightly lower than the OBS in most of the months except at Bonga, the results indicated that the model adequately replicates the annual cycle of surface wind speed (Figure 2). For both OBS and ERA, the annual cycles of the wind speed in the GoG show bimodal peaks; the first/secondary peak was recorded in February and the second/primary peak in August. The secondary peak ranged between 3 ± 0.5 and 11 ± 0.6 ms^{-1} while the primary ranged between 4.07 ± 1.0 ms^{-1} and 14.5 ± 1.0 ms^{-1}

across the stations (Figure 2). In addition, the wind speeds were generally higher in the wet season (June to September) than in other periods of the year. The time of maximum wind speed coincided with the peak of the wet season and WAM (i.e., August to September) in the study region. This could be attributed to the fact that mesoscale convective complexes in tropical Africa are much more frequent at the peak of wet season in West Africa; the period when wave amplitudes have shown to be largest (Laing and Fritsch, 2000; Grist and Nicholson, 2001; Ogungbenro et al., 2015; Matthew and Ayoola, 2020). Also, the highest and the lowest offshore wind speeds were recorded at the farthest offshore location (*i.e.,* Agbami) and the nearest (*i.e.,* Bonny) to the coast, respectively. This finding further corroborates the assertion in previous study that sea surface wind speed increases with increasing distance to the coast (Wen et al., 2021).

Furthermore, performance evaluation of sea surface wind speed of ERA compared with buoy-station observations are presented in Table 1. The findings revealed that the temporal and spatial patterns of downscaled wind speed are highly consistent with the observation data. There were close agreements and fits between the ERA simulations and observations of the annual cycle of wind speeds at the five offshore locations. The model slightly underestimates both the daily and monthly observations of wind speed, except at Bonga station (Table 1). For example, the estimated mean biases (MB) in ERA daily wind speed were -0.07 (Forcados), -0.39 (Sea Eagle), -0.09 (Bonny), 0.91 (Bonga), and -0.28 ms^{-1} (Agbami), while the percentage biases (PMB) were -2.12, -7.06, -3.13, 17.45 and -2.76% at Forcados, Sea Eagle, Bonny, Bonga, and Agbami respectively. The root-mean-square error (RMSE) ranged between 0.89 and 3.71 ms^{-1}. As expected, the MB, PMB, and RMSE obtained with monthly datasets were lower than those of the daily. Also, the correlation coefficients ($0.52 \leq r \leq 0.96$) obtained for the monthly averages were positive and significant at three (3) out of the five (5) stations (i.e., 60% of the stations) while the values of Nash-Sutcliff Efficiency (NSE) ranged between ±0.62 and ±0.91, except at Bonga where NSE was found to be -0.39.

In general, the results indicated that the performance of ERA in simulating sea surface wind speed was satisfactory except at Bonga where the discrepancies in the model simulations were found to be significant at $p = 0.05$. Substantial discrepancies in the model simulations at Bonga could be attributed to potential noise in the model grid that falls within the station. In addition, the probable reason for the poor estimate might not be unconnected with the fact that a few stations fall within a relatively low wind speed region and simulation of sub-daily wind speed had been previously reported to be substantially different from the observations with the poorest performance, for regions and periods with wind speeds ≤ 3.84 ms^{-1} (Ayala et al., 2020; Matthew, 2022). In general, the findings suggested that ERA produces reliable sea surface wind speed suitable for assessment of wind energy potential (as done in this present study) and climate impact studies (to be carried out in future researches) over the study area.

3.2 Buoy-station observations and ERA simulations of wind characteristics

The estimated Weibull shape (*k*) and scale (*c*) factors at 100 m hub-height for both OBS and ERA are shown in Figure 3. The results showed that the wind speed characteristics obtained with ERA compared well with those of the OBS. The sea wind speed characteristics for both OBS and ERA were adequately captured by the Weibull shape (*k*) and scale factors (*c*).

The values of k for the OBS ranged between 5.5± 0.1 (at Forcados) and 9.8 ± 0.15 (at Bonny) while those of the ERA ranged between 4.5± 0.4 (at Bonga) and 9.2 ± 0.15 (at Bonny) (Figure 3a). The disparities between ERA and OBS followed the patterns previously obtained for the sea surface wind. As previously established in the literature, the values of *k* range between 1 and 10 over the study area (Ohunakin et al., 2011). The pattern of spatial distribution of *c* at the chosen hub height perfectly mimics that of the sea surface wind speed (Figure 3b). The value of *c* for the OBS at Agbami (17.5 ± 2.0 ms^{-1}) was found to be the highest and the lowest (6.6 ± 0.5 ms^{-1}) at Bonny. Similarly, *c* for ERA ranged between 17.2 ± 2.0 ms^{-1} at Agbami and 7.0 ± 0.5 ms^{-1} at Bonny (Figure 3b). As expected, the results demonstrated that the offshore wind speeds increase with height up to the chosen hub height.

3.3 Spatial and temporal variations in observed and simulated offshore wind power density

Table 2 describes the variations in wind power density (WPD) based on OBS and ERA at the selected offshore stations. The indicators used are minimum WPD, maximum WPD, CV, MIV, annual trend, distance of the station from the coast, and the episode of extreme wind speed at 100 m height (≥ 16 ms^{-1}). In order of their distances from the coast, Bonny is the closest while Agbami is the farthest (Table 2). The results demonstrated that the wind power potential in the GoG varied with the distance from the coast with Agbami showing the best potential for wind power resources. The maximum monthly mean WPD varied from 150.9 (Bonny) to 3092.6 Wm^{-2} (Agbami) for the OBS dataset and 164.0 (Bonny) to 2943.2 Wm^{-2} (Agbami) for the ERA simulation. On the other hand, the minimum monthly mean WPD varied from 150.8 to 3003.5 Wm^{-2} for OBS and 163.4 to 2873.3 Wm^{-2} for ERA (Table 2). However, typical of an offshore site, as documented in Kamranzad and Lin (2020) and Wen et al. (2021), the results of the present study showed low ranges (0.13 to 89.5 Wm^{-2} for the OBS and 0.61 to 69.89 Wm^{-2} for ERA) in the monthly WPD over the offshore locations (Table 2). The findings demonstrate that both CV and MVI values were very low. For example, the CV at the highest wind-producing location (i.e., Agbami) ranged from 0.005700 to 0.006291 while MVI varied from 0.016426 to 0.019985 for ERA and OBS datasets respectively (Table 2). The annual trends in WPD were found to be generally low and insignificant. In addition, the patterns and signs of the trends were the same but with slightly varying magnitudes for both OBS and ERA. It was negative at Sea Eagle, Bonga, and Agbami but positive at Forcados and Bonny. For example, the annual trends in the observed WPD were -0.00426 (Sea Eagle), -0.01069 (Bonga), -0.04516 (Agbami), 0.000984 (Forcados), and 0.000697 Wm^{-2} $year^{-1}$ (Bonny). The episodes of extreme wind speed were very low with 13% (OBS) and 12% (ERA) at Agbami during the SOP, and none in other locations. It has been previously established that the best offshore location should have the least variation indicators with the best accessibility (Jurasz et al., 2021). Low variability and intermittency obtained (in terms of trends, range, CV, MVI, and extreme wind speed episodes) are all indications of good wind power availability at the sites. In addition, relatively large mean monthly and annual WPD obtained over a few of the offshore stations are positive indications of high potentials for wind energy resources. The experience of Nigeria with existing offshore oil and gas exploitations and industries is a very strong factor that makes the buoy-stations accessible for efficient offshore wind power development as suggested in ANRC-AfDBG (2021). In summary, the results of the present study suggested that a few locations in the GoG is highly viable for offshore wind energy generation. We found that Agbami has the highest potential for offshore wind energy among the selected offshore locations. Hence, future investment in offshore wind energy project in the GoG is expected to significantly improve energy supply to meet the ever-increasing energy demand occasioned by population explosion and industrial revolution in West Africa.

Figure 4 illustrates the daily mean and annual total WPD at 100 m hub-height at the selected offshore stations in the GoG. The highest daily mean WPD (2.9 ± 0.5 and 2.8 ± 0.5 kWm^{-2} for OBS and ERA respectively) and annual total WPD (1.05 ± 0.17 and 1.02 ± 0.17 MWm^{-2} for OBS and ERA respectively) were obtained at Agbami, while Bonny recorded the least daily mean WPD (~ 0.2 ± 0.05 kWm^{-2} for both OBS and ERA) and annual total WPD (~ 0.05 ± 0.002 MWm^{-2} for both OBS and ERA). These results further confirmed the potential for offshore wind energy resources among the study stations. We found the farthest station, Agbami, to have the highest potential for wind power generation in the GoG.

4. Conclusions

This present study has utilized buoy-station observations of wind speed to validate the use of high-resolution RegCM4 Regional Climate Model CORDEX-CORE simulations driven by ERA-Interim for the assessment of wind energy potentials of some selected synoptic offshore stations from 1979 to 2015 in the Gulf of Guinea (GoG). It further adopted a series of standardized criteria such as wind power density (WPD), annual trends, coefficient of variation (CV), monthly variability index (MVI), accessibility, extreme wind speed, and distance to the coast, to determine the most suitable locations for offshore wind energy development over the study area. The study demonstrated that ERA has appropriate spatial and temporal resolution and fits the field measurements at most of the selected stations fairly well. Findings revealed that ERA produces reliable sea surface wind speed suitable for assessment of wind energy potential and climate impact studies in the GoG. The wind power potential varied with the distance from the coast with Agbami buoy-station showing the best potential for wind power generation. There were evidences of high potentials of wind energy resources (in terms of monthly and annual mean WPD) and very low and insignificant variability/intermittency (in terms of trends, range, CV, MIV and frequency of extreme wind speed episodes) at the selected locations, particularly at Agbami. It was also established that the offshore locations were very viable for future offshore wind power generation. The use of very few offshore buoy-stations, that appear to cluster around a narrow coastline, due to paucity of observational wind data is perceived to be a probable limitation of this present study. The findings have implications in offshore wind energy resources in the GoG as a dependable and efficient alternative energy source under future warming climate. It is recommended that further investigation should be carried out on the cost of investing in offshore wind energy project in the GoG.

5. Acknowledgments

The authors wish to acknowledge the support offered by Covenant University in the actualization of this research work.

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In-Situ Based Observation and Reanalysis-derived Wind Data for Offshore Wind Energy Potential in the Gulf of Guinea

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Declaration of competing interest

Authors declare that there are no known competing interests.

Figures

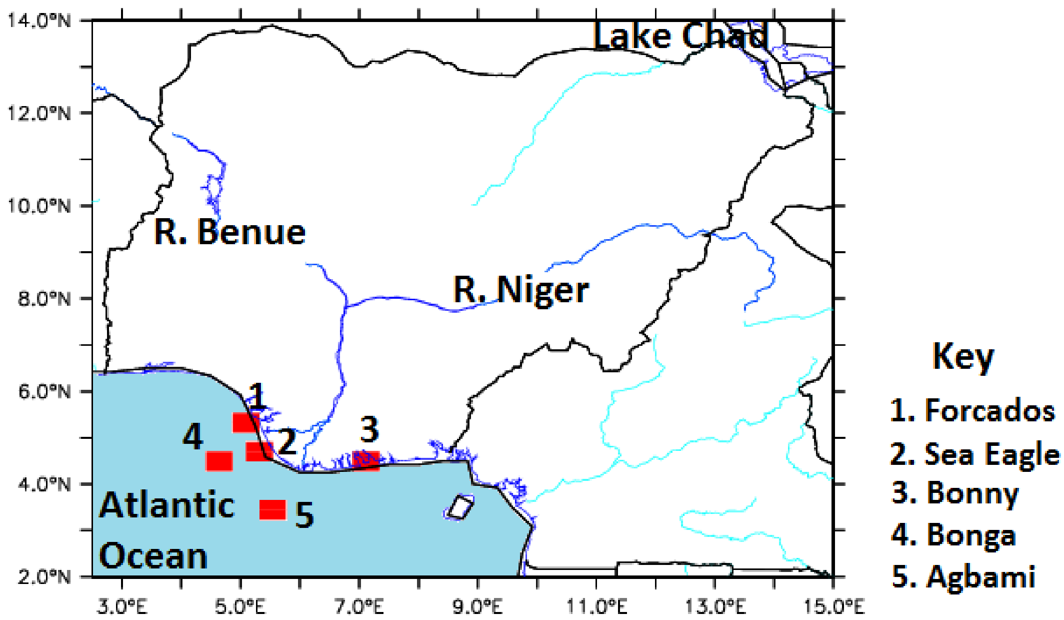

Figure 1: Geographical locations of the offshore sea-surface wind observation stations in the Gulf of Guinea used in this study (Adapted from Ohunakin et al., 2022)

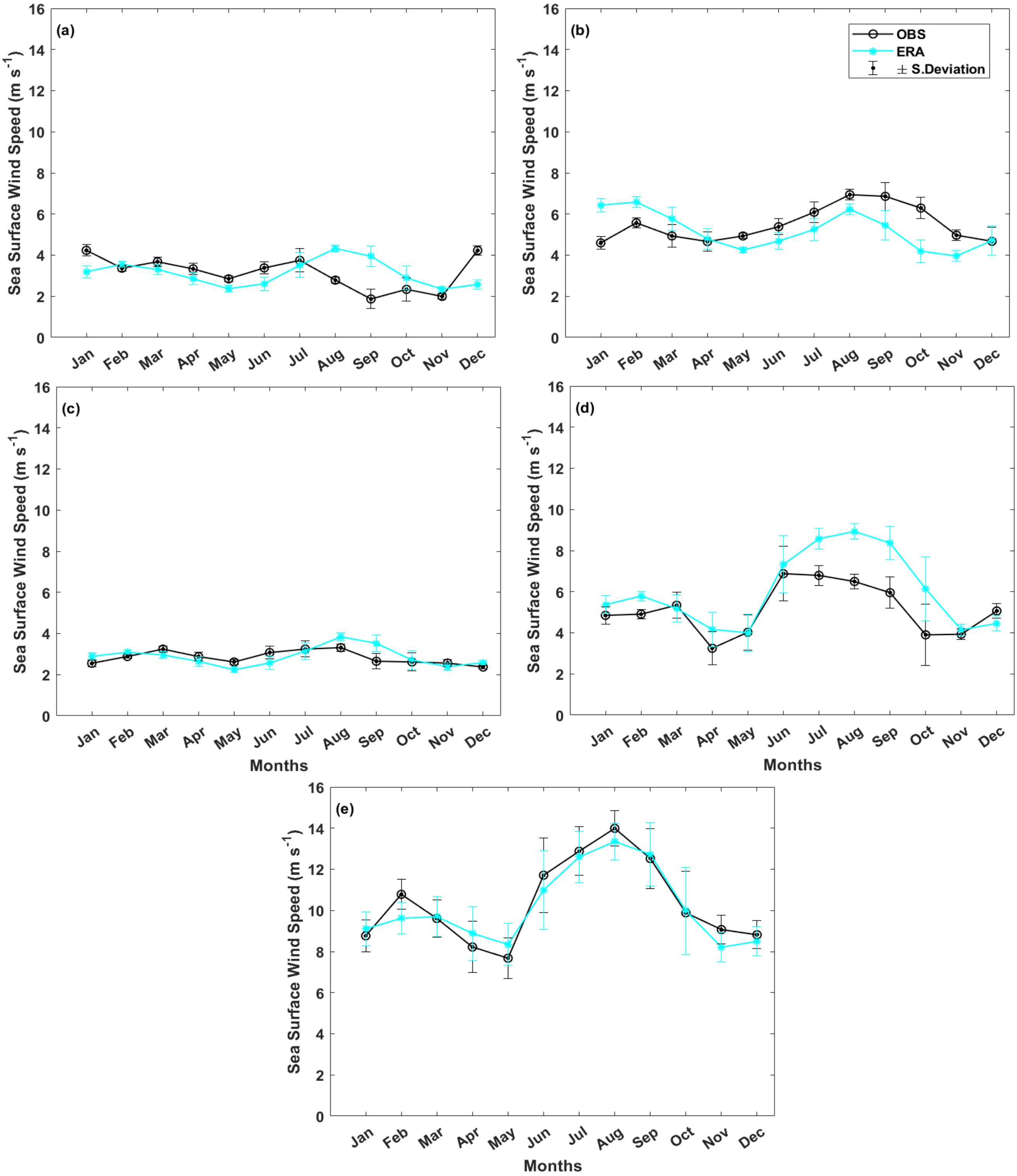

Figure 2: Ground Observations and Estimated Monthly means of Sea Surface Wind Speed at the Selected Stations in the Gulf of Guinea during the Stusy Period: (a) Forcados, (b) Sea Eagle, (c) Bonny, (d) Bonga, and (e) Agbami.

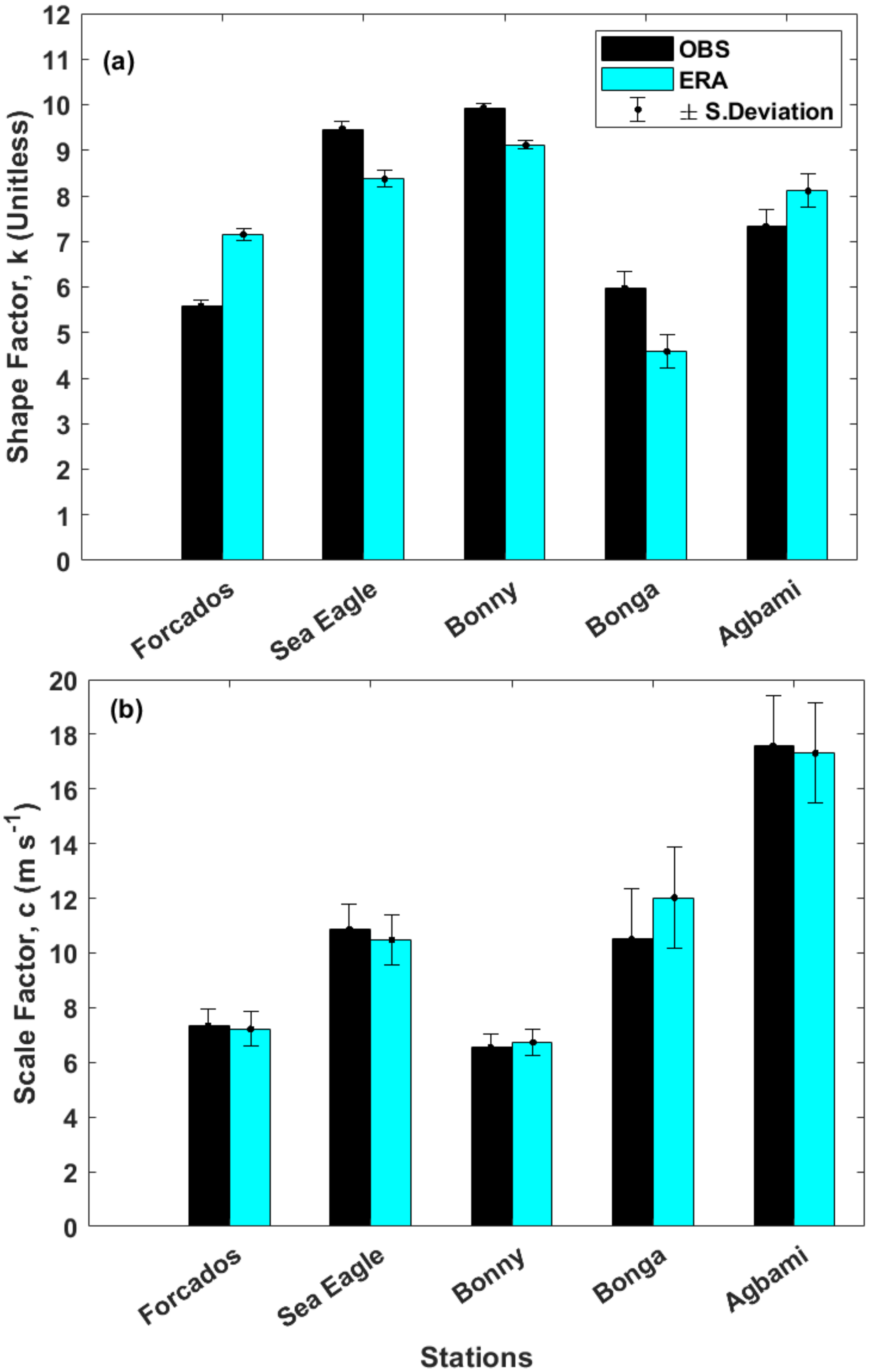

Figure 3: Observed (OBS) and Simulated **(**ERA) Means and Standard Deviations of the Weibull (a) Shape Factor k, and (b) Scale Factor, c of Wind Speeds at 100 m-Hub Height at the Selected Offshore Stations in the Gulf of Guinea.

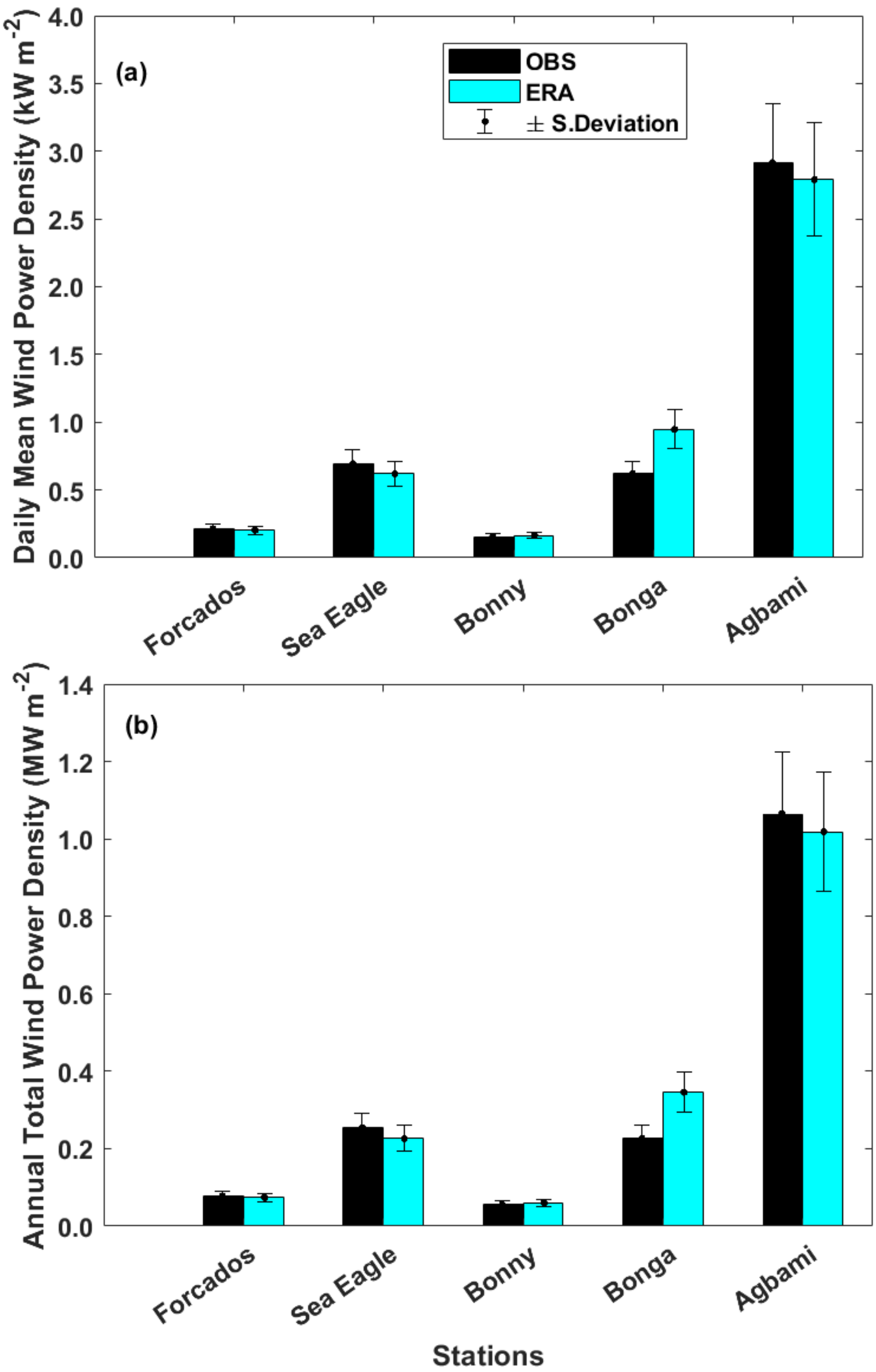

Figure 4: Observed, OBS and Simulated**,** ERA, (a) Daily mean Wind Power Density in kW m^{-2} and (b) Annual Total Wind Power in MW m^{-2} at 100 m-Hub Height at the Selected Offshore Stations in the Gulf of Guinea.

List of Tables

Table 1: Performance Evaluation of Sea Surface Wind Speed (in ms^{-1}) of ERA-driven Regional Climate Model with Ground Observations (OBS) at the Selected Stations.

Indices	Daily Datasets					Monthly Datasets				
	Forcados	**Sea Eagle**	**Bonny**	**Bonga**	**Agbami**	**Forcados**	**Sea Eagle**	**Bonny**	**Bonga**	**Agbami**
Mean of OBS	3.13	5.51	2.93	5.20	10.32	3.15	5.49	2.83	5.12	10.33
Mean of ERA	3.07	5.12	2.83	5.91	10.03	3.13	5.20	2.78	6.01	10.17
RMSE	1.51	1.61	0.89	2.60	3.71	1.01	1.10	0.39	1.37	0.59
MB	-0.07	-0.39	0.09	0.91*	-0.28	-0.02	-0.30	0.05	0.89*	-0.16
PMB	-2.12	-7.06	3.13	17.45*	-2.76	-0.76	-5.38	1.85	17.10*	-1.53
r	-0.39	0.10	0.24	0.04	0.22	-0.08	0.20	0.52*	0.83*	0.96*
NSE	-0.74	0.38	0.05	1.59	0.68	-0.75	0.82	0.62	0.39	0.91

** Significant at 0.05 significant level*

RMSE = root-mean-square-error
MB = mean bias
PMB = Percentage mean bias
NSE = Nash-Sutcliff efficiency
r = Correlation coefficient

Table 2: Values of Indicators of Variations in the Observed (OBS) and Simulated (ERA) Wind Power Density at the Selected Stations

Indicators of Variations	**Stations**									
	OBS					**ERA**				
	Forcados	**Sea Eagle**	**Bonny**	**Bonga**	**Agbami**	**Forcados**	**Sea Eagle**	**Bonny**	**Bonga**	**Agbami**
Maximum WPD (Wm^{-2})	213.35	707.21	150.93	638.95	3092.61	203.13	632.66	164.00	971.11	2943.19
Minimum WPD (Wm^{-2})	211.56	695.09	150.80	622.03	3003.46	201.44	620.37	163.39	938.83	2873.30
Range of WPD (Wm^{-2})	1.79	12.12	0.13	16.92	89.15	1.69	12.29	0.61	32.28	69.89
CV	0.001958	0.004216	0.000212	0.006029	0.006291	0.001766	0.004528	0.000759	0.008427	0.005700
MVI	0.005585	0.011739	0.000581	0.017944	0.019985	0.005555	0.013275	0.002521	0.022731	0.016426
Annual Trend (Wm^{-2} $year^{-1}$)	0.000984	-0.00426	0.000697	-0.01069	-0.04516	0.00139	-0.00333	0.00030	-0.01589	-0.04332
Distance from Coast (Referenced to the Coast of Warri in Nautical Miles)	On Coast	49	On Coast	72	131	On Coast	49	On Coast	72	131
Extreme Wind Speed (%)	-	-	-	-	13	-	-	-	-	12

* *Significant at 0.05 significant level*

WPD = Wind power density
CV = Coefficient of variation
MVI = Monthly variability index

COVERING LETTER

Subject: **Submission of manuscript**

Dear Editor,

I would like to submit the following manuscript for possible evaluation

Manuscript Title: **In-Situ Based Observation and Reanalysis-derived Wind Data for Offshore Wind Energy Potential in the Gulf of Guinea**

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I affirm that the manuscript has been prepared in accordance with your “Journal of Cleaner Production” guide for authors.

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Thank you.

Olayinka S. OHUNAKIN