Exploration of Wind-Wave Energy Potentials for Renewable Energy Development in Parts of Ondo Coastal and Offshore Locations, Southwestern Nigeria

P. A. Enikanselu, A. A. Balogun, T. Ewetumo, A. A. Osinowo, M. O. Ogundare, O. R. Ashiru, J. S. Abe, A. S. Ifanegan, B. A. Okunlola

Abstract: ***The study explored wind-wave energy distribution in parts of Ondo State coastal and offshore locations, Nigeria. This was to identify suitable locations for the deployment of wind turbines and wave energy converters (WEC) for the government's proposed renewable energy initiative in the area. It involved the use of daily, one-hourly averaged wave height, wave period, and 10m wind speed data spanning from January 1, 1989, to December 31, 2023, derived from ERA5 reanalysis data sets. The wave height and wave period data were used to compute the wave power density, while the 10m wind speed data was used to estimate the wind power density. The two-parameter Weibull distribution function with the gamma function were used to compute the wind power density. The threshold condition of wave power density above 6 kW/m and a coefficient of variation below 2.0 was used to determine the relatively rich energy regions of wave power. Also, the wind power classification was used to determine the class of dominant wind power in the area. Results revealed that the wave power varied from 0.01–4.57 kW/m, while the wind power varied from 7.66–83.43 W/m². The southwestern part of the study area (offshore) exhibited the largest wind power density. The studied locations were adjudged unsuitable for large-scale wind-wave energy generation. The energy potentials could only be adequate for non-grid-connected electrical and mechanical applications. However, probing deeper offshore could detect bankable regions of wind-wave energy deposits.***

Keywords: ***ERA5 Reanalysis Data, Renewable Energy, Wave Energy Converter, Wind Turbines.***

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***Correspondence Author(s)**

Enikanselu Pius Adekunle, Professor, Department of Applied Geophysics, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo, Nigeria. Email ID; paenikanselu@futa.edu.ng

Balogun Ahmed Adedoyin, Professor, Department of Meteorology and Climate Science, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo, Nigeria. Email ID: aabalogun@futa.edu.ng

Ewetumo Theophilus, Associate Professor, Department of Physics, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo, Nigeria. Email ID: ewetheo66@gmail.com

A. A. Osinowo*, Department of Marine Science, Federal University of Technology Akure, Ondo State, Nigeria. Email: aaosinowo@futa.edu.ng, ORCID ID: 0000-0002-0270-9051

Margaret Ojone Ogundare, Department of Marine Science and Technology, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo, Nigeria. Email ID: moogundare@futa.edu.ng

Ashiru Olusola Raheemat, Department of Marine Science and Technology, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo, Nigeria. Email ID: orashiru@futa.edu.ng, ORCID ID: 0000-0002-7316-6939

James Sunday. Abe, Senior Lecturer, Department of Marine Science and Technology, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo, Nigeria. Email ID: Jsabe@futa.edu.ng

Ayomide Samson Ifanegan, Assistant Lecturer, Department of Applied Geophysics, Federal University of Technology Akure, Ondo State, Nigeria. Email: asifanegan@futa.edu.ng, ORCID ID: 0009-0004-3622-2454

Babatande Abraham Okunlola, Department of Marine Science and Technology, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo, Nigeria. Email ID: baoknnlula@futa.edu.ng

I. INTRODUCTION

The attention dedicated to the utilization of renewable energy resources has increased dramatically in recent years. The maritime environment houses a vast supply of renewable energy and has great potential for the development of renewable energy projects. Ocean resources are clean energy sources with significant potential over large areas, as evidenced by tidal currents and ocean surface waves [1].

It is also possible to harness wind energy in these locations. However, offshore wind farms involve higher construction and maintenance costs [2].

Promoting the combined harvesting of wind and wave energy resources, either through hybrid devices or co-located wind-wave farms, could present an opportunity to counteract this shortcoming and offset significant costs [3].

[4] Conducted a study on hybrid marine energy projects in Europe and discovered that, due to their abundant resources and suitable depth conditions, the north and west have the most potential for combination technologies. Numerous studies have been conducted to evaluate the wind-wave energy potential in different parts of the world [5], but very few have emphasized how these resources might be utilized in tandem [6]. Current research on the combined exploitation of wind and offshore waves indicates that this is a viable option in several European and global locations [7]. Additionally, several studies have estimated how these resources relate to one another and enhance economic competitiveness.

Offshore wind resources offer more benefits than land-based wind resources [8]. Among all marine renewable technologies, wind energy from offshore sources is the most advanced in terms of installed capacity, commercialization, policy frameworks, and technological advancement [9]. The development of new offshore solutions, such as wind turbines with larger rotors, deep-sea locations, and floating platforms, is currently the main focus of concern [10]. Floating technology can be viewed as a commercially viable way to harness readily available wind resources, particularly at greater depths (>50 m), where traditional fixed offshore wind turbines are no longer economically feasible [11]. Wave energy converters (WECs) have been identified as devices with the potential to play a significant role in the medium to long term [12]. While wave power generation is the primary reason for utilizing and exploiting wave energy, it can also be used for heating, desalination, pumping, and other applications [8].

Several authors have investigated the feasibility of combining floating wind turbines with WECs. Wind-wave technology is a sustainable solution for reducing the sporadic availability of wind and wave resources, thereby improving a site's overall marine energy potential [13]. As a result, the integration of combined renewable energy technologies helps lower energy costs and reduce power fluctuations [14].

[15] Examined, based on a literature review and data from Africa Energy Outlook 2019, the feasibility of adopting renewable energy from the ocean for socioeconomic development in sub-Saharan Africa, given the region's enormous potential for ocean-based energy sources. Numerous studies have recently detailed the possible geographical impacts of renewable energy instruments on the oceans [16].

There are regions in the Mediterranean where wind-wave energy exhibits low mean values, but they are not negligible. The Gulf of Lions, the Sicily Straits (Central Mediterranean), the Sardinian beaches, the northeastern coasts of the Balearic Islands (NW Mediterranean), and specific spots in the Aegean Sea are also promising areas for joint exploitation.

The Ondo coastal environment is part of the Atlantic Ocean and is endowed with abundant wind-wave energy resources. The area is, therefore, one of the proposed locations for the development of renewable energy. Nigeria plans to generate 30,000 MW of electricity by 2030, with 3,000 MW coming from renewables and 27,000 MW from its power plants to serve its population of over 200 million. However, power generation currently hovers just above 5,000 MW. At present, little to no studies have been conducted on the wind-wave energy potential in the study area. The dwindling oil resources in Nigeria have necessitated the consideration of the area for the exploration of bankable wind-wave energy potentials. Renewable energy is environmentally friendly and reliable.

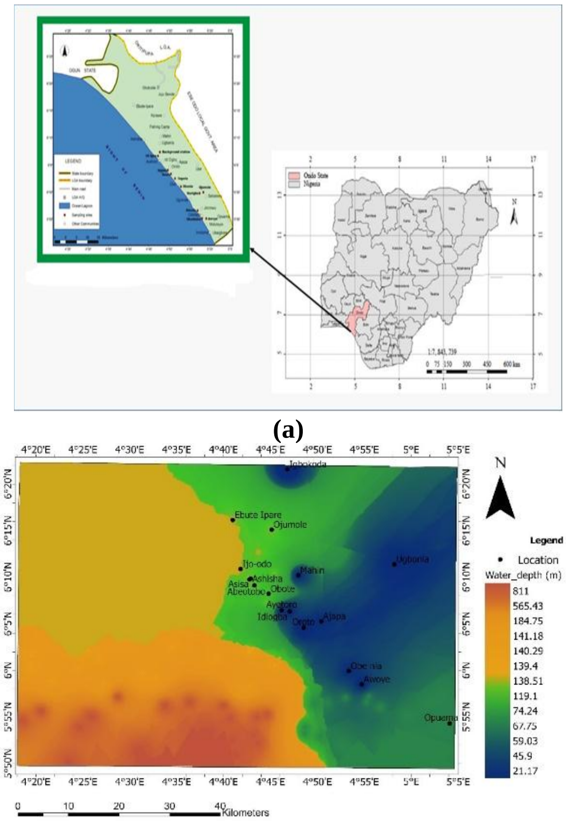
This study, therefore, evaluates the potential of wind and wave energy and estimates areas viable for the combined exploitation of both resources in the region. It is intended to provide the required baseline information for harnessing wind-wave energy in the study area to generate steady, cheaper, and sustainable electricity through an environmentally friendly process. Investment in this project is expected to improve power supply, enhance socioeconomic activities, attract investors, and create employment opportunities. These attributes of renewable resources are analyzed in the present study using reanalysis data for both wind and wave conditions of the sea states. Furthermore, the bivariate distribution of wave energy is analyzed, and an investigation is conducted to identify sites with relatively rich wave energy, ideal for the installation of wave power plants for electrical energy generation.

This work is organized as follows: Section 2 provides detailed information about the study region. The analytical methods used to evaluate wind and wave power in the study region, followed by the results and discussion, are presented in Sections 3 and 4, respectively. Finally, Section 5 concludes the work.

II. DESCRIPTION OF THE STUDY AREA

A. Geography and Topography of the Study Area

Figure 1a illustrates the study area, which is located between latitudes 5.83°N and 6.3°N and longitudes 4.3°E and 5.08°E.



(a)

(b)

[Fig.1: (a): Location Map and (b) Topography of the Study Area]

There are two main seasons in the tropical environment, with the rainy season lasting approximately seven months (April to October) and the dry season lasting roughly four months (November to March) [17]. The area's coastal regions typically feature rainforest-type flora, with an abundance of trees and grasses growing along riverbanks. The environment is characterized by high-energy waves, which have resulted in incessant sea incursions into inhabited areas [18]. The hydrological setting of the study area is Niger River-dependent and drains a significant portion of West Africa with sediment-laden water, which empties into the Atlantic Ocean through 14 major river inlets [19]. Due to its low-lying, predominantly flat topography (Fig. 1b), the region is highly vulnerable to coastal erosion and flooding, particularly during high tides [20].

B. Rainfall Pattern and Geology of the Study Area

The Ondo state coastal region is known for heavy precipitation varying from about 2,000 mm/annum in Irele and Okitipupa environs to about 3,000 mm/annum in Ilaje and Ese-Odo areas [21]. The Coastal Plain sands constitute the major shallow hydro-geologic units in the area. Aquifers are characteristically continental sands, gravels, or marine sands. The lateritic earth overlying the sands, as well as the underlying impervious clay/shale member of the Akinbo Formation, constitute protective configuration for the aquifer units [22]. Surface geology in this coastal area is made up of the Benin formation and also the recent alluvium. The heterogeneous and loose nature of the Benin formation makes water table to occur at fairly deep depth beyond the reach of most ordinary hand-dug wells [23].

III. DATA SOURCE

The primary source of data used for this study is the ERA5 Reanalysis, spanning a 34-year period (1989–2023). The choice of ERA5 is based on previous works that highlight its relevance in African regions. The dataset is highly reliable and up-to-date, providing hourly, synoptic, daily, and monthly data fractions for trend analysis and ocean weather monitoring and forecasting, particularly over data-sparse regions like Africa [24].

The data were downloaded over a box extending from latitudes 5.83°N to 6.3°N and longitudes 4.3°E to 5.08°E at a 0.5° × 0.5° spatial grid resolution (Figure 1a).

IV. METHODOLOGY

The method of study involved using 1-hour values of significant wave height and wave period to compute wave power density, followed by the computation of wind power density using 10m wind speed data. The parameters (significant wave height, wave period, and 10m wind speed) were extracted from both buoy (observational) data and ERA5 Reanalysis.

Wave power density was estimated from significant wave height and wave period using Equation 1.

$$P_w = \frac{\rho g^2}{64\Pi} H^2{}_{mo} T_e = 0.49 H^2{}_{mo} T_e \quad \dots \quad (1)$$

where P_w is wave power (kW/m), H_{mo} is the wave height (m), and T_e is the wave period (s).

Additionally, the wind power density was computed using equation 2 [25].

$$P_d = \frac{P(v)}{A} = \frac{1}{2}\rho \int_0^\infty v^3 f(v) dv = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad \dots \quad (2)$$

Where A is the swept area of the wind turbine rotor (W/m^2), Pd is the wind power density (W/m^2), P (v) is the wind power (watts), and ρ is the air density, typically taken to be 1.225 kg/m^3.

Where,

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

$$c = \frac{\bar{v}}{\Gamma(1+1/k)} \quad \dots \quad (4)$$

$$\Gamma(x) = \int_0^\infty \exp(-u) u^{x-1} dx \quad \dots \quad (5)$$

$$k = -\left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad \dots \quad (6)$$

for 1 ≤ k ≤ 10

The wave power stability was determined using the Seasonal Variability Index (SVI) and the Monthly Variability Index (MVI) in Equations 7 and 8, respectively.

$$SVI = {(P_S1 - P_S4)}/{Pyear} \quad \dots \quad (7)$$

and the MVI is expressed as:

$$MVI = {(P_M1 - P_M12)}/{Pyear} \quad \dots \quad (8)$$

Where *P*s1 and *P*s4 are the maximum and minimum seasonal mean wave power densities, respectively, P_M1 and P_M12 are the maximum and minimum monthly mean wave power densities, respectively, and *P*year is the annual mean wave power density. Higher index values indicate larger wave energy variations and decreased stability compared to lower index values.

The wind coefficient of variation (COV) was estimated using equations 9 and 10. The formula is as follows:

$$COV = \frac{s}{\bar{x}} \quad \dots \quad (9)$$

Where s is the wind standard deviation (STD) and is evaluated as:

$$S = \sqrt{\frac{\sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i\right)^2/n}{n-1}} \quad \dots \quad (10)$$

$\bar{x}$ is the mean value.

According to [28], the threshold conditions for determining the relatively rich energy region of wave power density were established: the average wave power density must exceed 6 kW/m, and the coefficient of variation must be less than 2.0. It is an interpretational tool developed by [26]. For the purpose of this study, an in-house MATLAB code was developed to identify the relatively rich wave power energy regions in the study area.

Additionally, another in-house MATLAB code was written to determine the bivariate distribution of wave energy in the study area.

For the purpose of this study,

Equation 11 was used to calculate the annual, seasonal, and monthly wave power density (WVPD). It is expressed as a percentage cumulative frequency as follows:

$$f(WVPD) = 100\left({}^{n}/_{N}\right) \quad \dots \quad (11)$$

Where N is the total of the WVPD values and n is the frequency of WVPD that satisfies each of the stated intervals of WVPD with respect to various wave powers.

For the purpose of validating the ERA5 Reanalysis data, the accuracy of the wave parameters from ERA5 Reanalysis was evaluated through conventional statistical analysis, consisting of the correlation coefficient, mean bias error, and root mean square error. These are given by Equations 12, 13, and 14, respectively [27]:

$$cc = \frac{\sum_{i-1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i-1}^{n}(x_i - \bar{x})^2 \sum_{i-1}^{n}(y_i - \bar{y})^2}} \quad \dots \quad (12)$$

$$Bias = \bar{y} - \bar{x} \quad \dots \quad (13)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i-1}^{n}(y_i - x_i)^2} \quad \dots \quad (14)$$

where x_i represents the buoy data, y_i represents ERA5 Reanalysis data, x and y are the mean values of buoy and ERA5 Reanalysis data and N is the total number of observations.

V. RESULT AND DISCUSSION

Table I presents the percentage cumulative frequency of the annual, seasonal, and monthly wave power density (WVPD) in the study area, as computed using Equation 11. It shows the annual, seasonal, and monthly percentage cumulative frequency distribution of wave power between 0 and 40 kW/m.

It was observed that the frequency of wave power values clusters around 0 to 5 kW/m, with occasional bursts of higher wave power across the area. Additionally, the wave power within the 0 to 5 kW/m range is higher during the dry season than the wet season over the majority of the locations.

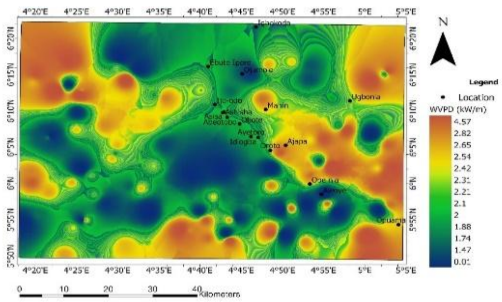
However, higher wave power (5 - 10 kW/m) between June and October is more frequent during the wet season. It can be inferred that lower wave power occurrences prevail in the dry season, while higher wave power occurrences are more prominent in the wet season.

Figure 2 shows the spatial distribution of the annual and seasonal mean wave power density (WVPD). From Figure 2a, it can be observed that the annual WVPD varied between 0.01 and 4.57 kW/m. The high range (2.42–4.57 kW/m) of WVPD occurred around Ajapa, Opuama, Mahin, and the North-West, North-East, and South-East flanks of the study area.

The WVPD distribution in the dry season (Figure 2b) revealed the same trend as the wet season (Figure 2c). However, the wave power is stronger in the wet season. The wave power density still reflects the mean annual distribution in the study area. Wave energy converters for domestic purposes can be deployed in these identified areas.

Table 1: Percentage Cumulative Frequency (*f*) Distribution of the Annual, Seasonal and Monthly Wave Power Values for the Study Area

	0≤wvpd≤5	5≤wvpd≤10	10≤wvpd≤15	15≤wvpd≤20	20≤wvpd≤25	25≤wvpd≤30	30≤wvpd≤35	35≤wvpd≤40	wvpd≥40
Annual	89.84	8.57	1.22	0.25	0.07	0.03	0.01	0.01	0.00
Dry Season	96.70	3.02	0.25	0.02	0.00	0.00	0.00	0.00	0.00
Wet Season	84.98	12.50	1.90	0.42	0.12	0.05	0.02	0.01	0.00
Jan	98.65	1.21	0.05	0.00	0.00	0.00	0.00	0.00	0.00
Feb	99.30	0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar	97.11	2.63	0.14	0.02	0.00	0.00	0.00	0.00	0.00
Apr	93.47	6.35	0.18	0.00	0.00	0.00	0.00	0.00	0.00
May	89.07	9.60	1.10	0.13	0.01	0.00	0.00	0.00	0.00
Jun	82.18	15.48	1.98	0.30	0.06	0.00	0.00	0.00	0.00
Jul	77.98	17.37	3.39	0.80	0.24	0.08	0.04	0.01	0.00
Aug	83.05	13.97	2.20	0.39	0.15	0.07	0.04	0.02	0.00
Sep	83.46	12.64	2.52	0.83	0.30	0.13	0.06	0.03	0.01
Oct	85.47	11.92	1.90	0.47	0.06	0.03	0.03	0.01	0.00
Nov	90.97	7.91	1.03	0.09	0.00	0.00	0.00	0.00	0.00
Dec	97.26	2.59	0.05	0.00	0.00	0.00	0.00	0.00	0.00



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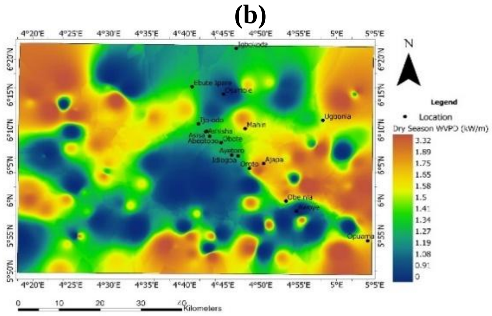

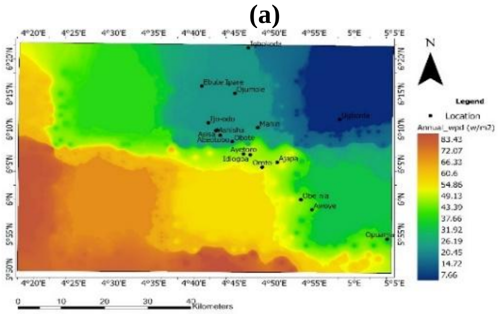

(c)

Fig.2. (a) Annual, (b) and (c) Seasonal Mean WVPD in the Study Area

Table II shows the monthly mean values of the wind parameters: shape (k), scale (c), wind power density (WPD), and wind speed (u). These values reflect the wind pattern in the area. It can be observed that the wind is more stable in August (the peak of

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the rainy season) and most erratic around October and February. Additionally, the high value of c is observed in August, while the lowest values occur around November and January. The minimum value of covariance occurs in August, supporting the maximum value of k in the same month and indicating the degree of stability of the wind in the area. This trend is also supported by the high values of the WPD ratio and wind speed ratio, whereas the values are lowest between November and January. The wind strength is highest during the rainy season and weakest during the dry season.

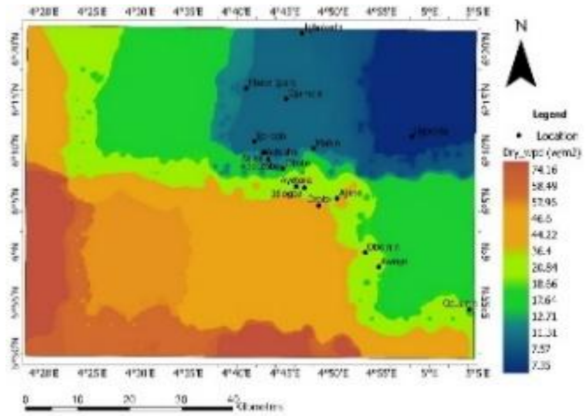
Table 2: Monthly and Annual Mean Wind Characteristics

Month	k	c (m/s)	WPD (w/m^2)	u (m/s)	σ	cov (%)	WPD Ratio	u Ratio
Jan	3.06	3.67	35.85	3.28	1.22	37.84	0.88	0.96
Feb	3.64	4.06	46.50	3.67	1.20	33.50	1.14	1.07
Mar	4.15	4.27	51.61	3.88	1.07	28.29	1.27	1.13
Apr	3.68	3.99	43.38	3.61	1.11	31.51	1.07	1.05
May	3.06	3.36	27.84	3.01	1.09	37.41	0.68	0.88
Jun	3.20	3.58	33.61	3.21	1.12	36.08	0.83	0.94
Jul	4.15	4.48	61.56	4.08	1.14	29.00	1.51	1.19
Aug	5.00	4.80	73.25	4.41	1.07	25.03	1.80	1.29
Sep	3.61	3.98	44.24	3.59	1.14	32.86	1.09	1.05
Oct	2.93	3.13	23.14	2.80	1.05	38.87	0.57	0.81
Nov	3.13	3.04	20.82	2.73	0.97	36.70	0.51	0.79
Dec	2.99	3.30	26.73	2.96	1.10	38.11	0.66	0.86
Annual			40.71	3.44				

On the other hand, Figure 3 shows the distribution of the annual and seasonal wind power density (WPD). The annual WPD varied from 7.66 to 83.43 W/m². The spotted highs are located around the southwest and southern flanks of the study area. The northeast flank revealed low WPD values in contrast to the WVPD counterparts. The previously identified coastal settlements and low-lying locations recorded low values of WPD. The near-bankable wind locations are located offshore to the southwest. However, only domestic wind turbines are recommended for deployment in the area. By standard classification, the area falls under class 1 (Table III).

Table 3: Wind Power Classification [28]

Power Class	Power Density (w/m^2) at 10 m
1	$0 < P \leq 100$
2	$100 < P \leq 150$
3	$150 < P \leq 200$
4	$200 < P \leq 250$
5	$250 < P \leq 300$
6	$300 < P \leq 400$
7	$400 < P \leq 1000$



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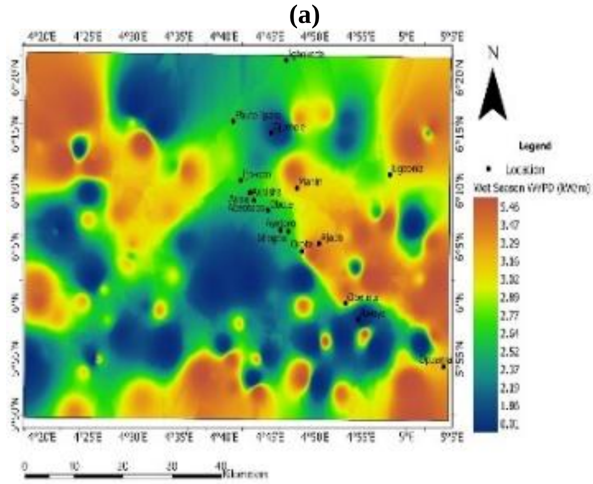

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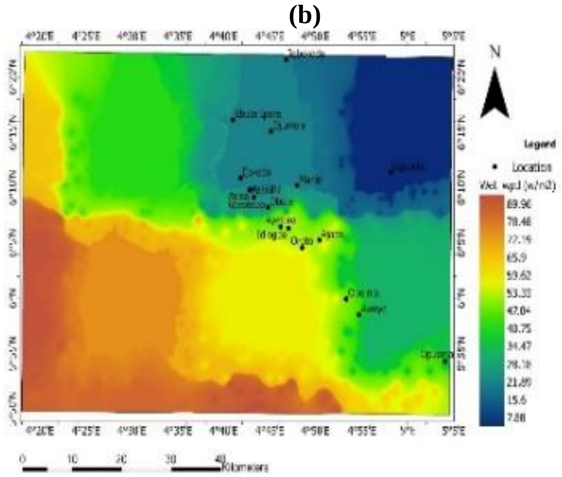


(c)

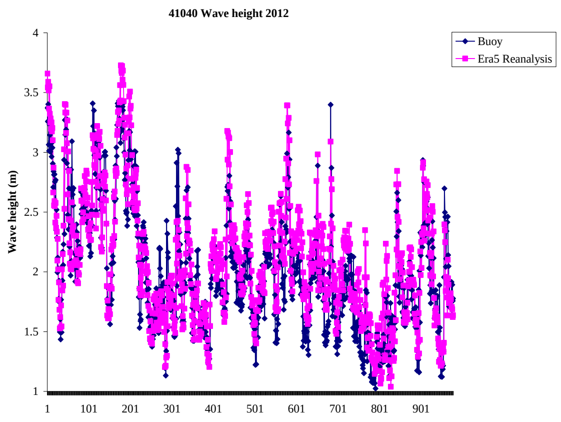
[Fig.3: (a) Annual, (b) and (c) Seasonal Distribution of WPD for the Period 1989-2023]

The wind power, like the wave power density, is stronger during the wet season than the dry season.

Figure 4 is a plot of time series and scatter plots of wave height (a), wave period (b), and 10m wind speed (c). These parameters were extracted from ERA5 Reanalysis sites over the buoy coordinates. They are meant to compare ERA5 Reanalysis data with the buoy data.

Qualitatively, there is a visual correlation between ERA5 Reanalysis and the buoy data. Quantitatively, it is evident in the scatter plot (Figure 4) that the parameters from ERA5 Reanalysis and their observed values are highly correlated, with the correlation coefficient (cc) larger than 0.8 for the three cases and significant at the 99% level. The calculated negative mean bias errors (MBE) of -0.09 m, -1.28 s, and -0.27 m/s show that the ERA5 Reanalysis data are slightly higher than the buoy data. The errors of ERA5 Reanalysis, which are 0.22 m, 1.36 s, and 0.55 m/s, are low when analyzed using the root mean square error (RMSE).

In general, the ERA5 Reanalysis data are consistent with the observations, showing that ERA5 Reanalysis can well reproduce the above parameters and represents a reliable data source for wind and waves.



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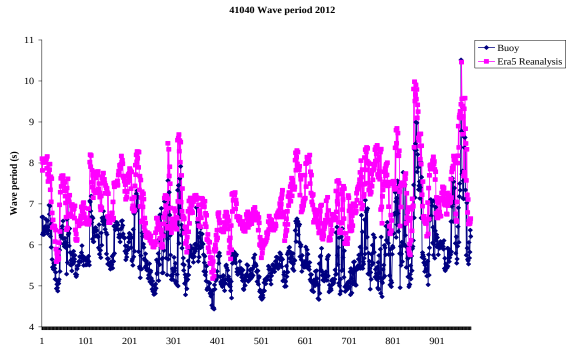

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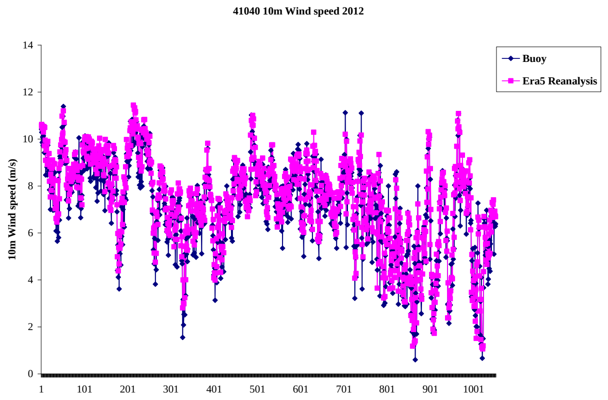
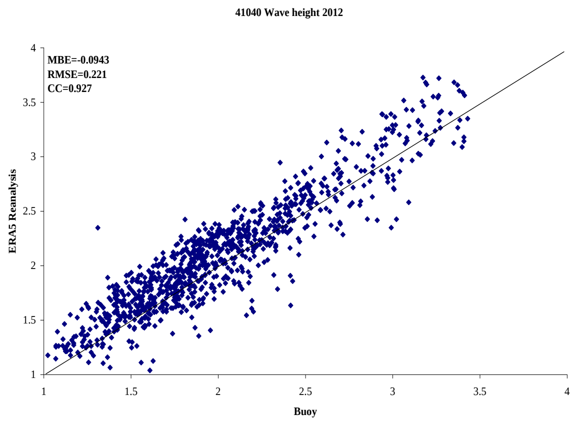
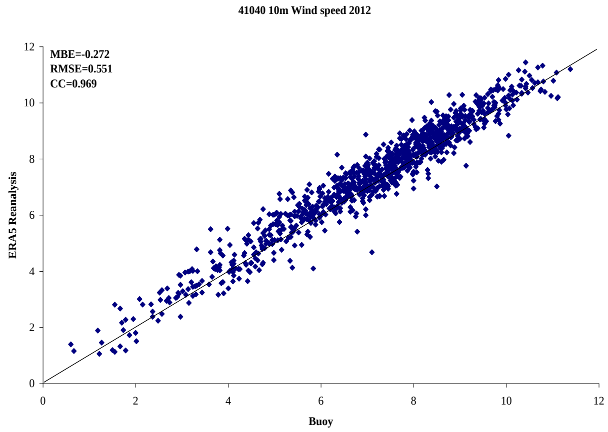
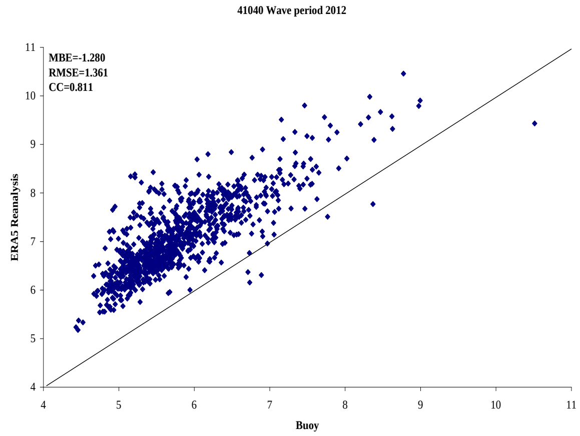


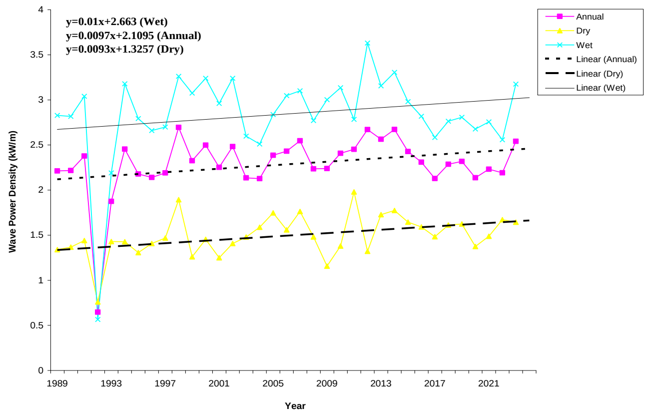
(c)

[Fig.4: Time Series and Scatter Plots of (a), Wave Height (b), Wave Period and (c), 10 m Wind Speed]









[Fig.5: Annual and Seasonal Temporal Trends in WVPD for the Period 1989-2023 Over the Study Area, Unit: kW/myr^{-1}]

Figure 5 presents the long-term temporal trends in wave power density (WVPD) for the period 1989–2023 over the study area. It explains the annual and seasonal temporal variations in wave power for the years considered. The annual trend is 0.0097 kW/myr^{-1}, while the trends during the dry and wet seasons are 0.0093 kW/myr^{-1} and 0.01 kW/myr^{-1}, respectively. The trend is stronger during the wet season. The minimum values of wave power for the year, dry season, and wet season are 0.64 kW/m, 0.75 kW/m, and 0.56 kW/m, respectively.

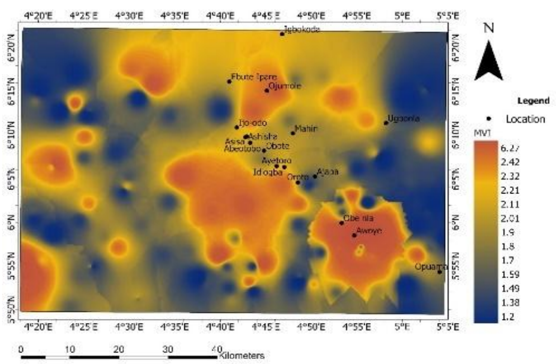
The annual maximum values of wave power for the year, spanning between the dry and wet seasons, are 2.69 kW/m, 1.97 kW/m, and 3.62 kW/m, respectively. These values occurred in the years 1998, 2011, and 2012. The increasing trend in wave power over the years and seasons can be attributed to the significant influences of storminess, atmospheric circulation, and monsoonal variation. Between the years 1991 and 1993, the abrupt fall and rise in wave power are associated with hurricane intensity and storminess in the basin, accompanied by the weakening and strengthening of the West African Monsoon.

Figure 6 is a map displaying the spatial variation of the variability index of wave power. It describes the pattern of wave power stability in the study area. The high Monthly Variability Index (MVI) and Seasonal Variability Index (SVI) regions are located around the North Central, Southeast, Central, and a few patches around the Southwest of the study area. A larger portion of the study area (blue) denotes regions of the highest stability of wave power.

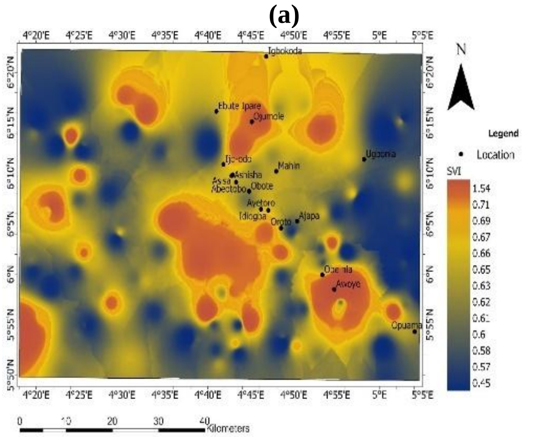
For both the MVI and SVI shown in Figure 6, the wave power is least stable along the coast, in locations around Ebute Ipare, Ojumole, Obe nla, Awoye, Ijo-odo, and Opuama, as well as in a few regions offshore. For these locations, the MVI varies between 2.42 and 6.27, and the SVI varies between 1.2 and 1.54. The greatest stability (1.2–1.3 for the MVI and 0.45–0.5 for the SVI) is found in waters north and south of Ugbonla, sporadic regions offshore, and in the extreme northwest of the study area.

For the variability indexes presented in Figure 7, wave power is most stable in the years 2005 and 2011, with values of 0.9 and 0.37, respectively, for the MVI and SVI.

For the MVI, the peak stability occurred in year 1992 with a value of 2.6, while for the SVI, the least stability occurred in the year 2012 with a value of 0.89.

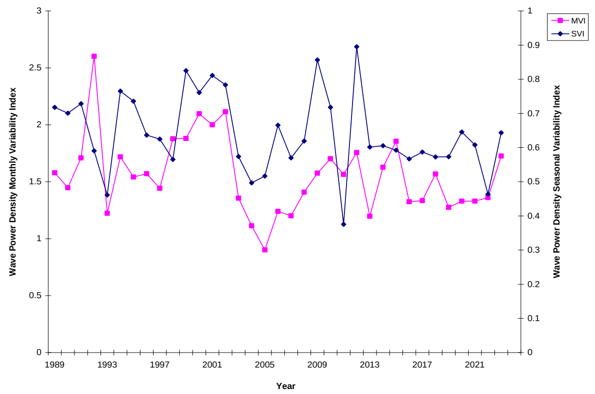


(a)



(b)

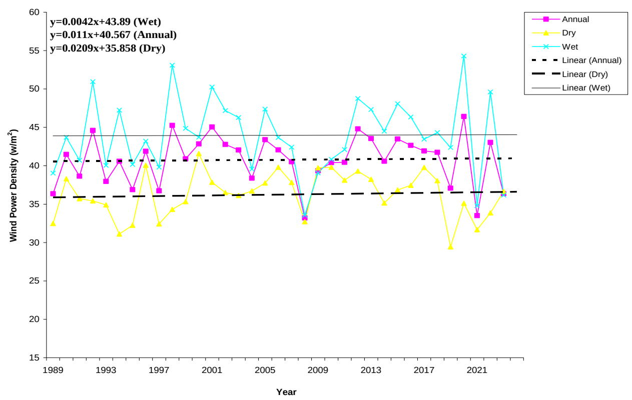
[Fig.6: Spatial Variation of Wave Power Variability Index in the Study Region]



[Fig.7: Temporal Variation of Wave Power Variability Index in the Study Area]

Figure 8 is a plot of annual and seasonal temporal trends in WPD for the period 1989-2023. The WPD generally showed increasing trends for the year and seasons. The annual trend is 0.011 W/m²/yr, while the trends during the dry and wet seasons are respectively 0.021 W/m²/yr and 0.004 W/m²/yr. The trend is stronger during the dry season.

For the annual and wet season averages, the WPD is minimum in the year 2008, with respective values of 33.19 W/m² and 33.55 W/m², while the largest values of 46.4 W/m², 41.5 W/m², and 54.2 W/m² are respectively found for the annual, dry, and wet seasons. Peak values of WPD for both the annual and wet season occurred in the year 2020, while for the dry season, it occurred in the year 2000.



[Fig.8: Annual and Seasonal Temporal Trends in WPD for the Period 1989-2023 Over the Study Area (w/m²yr⁻¹)]

Table IV shows a bivariate distribution of wave height (H_s) and wave period (T_e) in the study location. It can be seen from the table that the most frequent sea states (bold and highlighted in green) concentrate between 3.5 s and 8.5 s for T_e and values ≤ 5 m for H_s.

Table 4: Number of Occurrences of Different Sea States in the Study Area

Hs/Te	1-3.5	3.5-6	6-8.5	8.5-11	11-13.5	>=13.5
0-2.5	0.11	**11.19**	**2.56**	0	0	0
2.5-5	0	0	**0.04**	0	0	0

A scatter table is frequently used to display the frequency of occurrence of sea states defined by a characteristic wave height (H_s)

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and wave period (T_e) [29]. The total annual wave power for different sea states is presented in Table V [30]. It can be seen that the main wave energy (bold and highlighted in green) [31] is also concentrated between 3.5 s and 8.5 s (T_e) and for values $\leq$ 5 m (H_s) [32]. When relating these results to the number of occurrences (Table V) [33], it is observed that the most frequent sea states coincide with the most energetic sea states [34].

Table 5: Total Wave Power (in GW/m) Corresponding to sea States for Different Ranges of H_s and T_e in the Study Area

Hs/Te	1-3.5	3.5-6	6-8.5	8.5-11	11-13.5	>=13.5
0-2.5	146316	5415184	463474	438	0	0
2.5-5	0	24	1225	0	0	0

VI. CONCLUSION

This study explored the wind-wave energy resources over parts of Ondo State's coastal and offshore locations, using 34 years of ERA5 Reanalysis data. The average wave power density varied from 1.01 to 4.57 kW/m, while wind power density ranged from 7.66 to 83.44 W/m². Areas of relatively high and low wave power stability were nearly evenly distributed across the study area. The shape parameter "k" indicated that the wind is most stable in August and least stable in October. Therefore, August is the most appropriate month for stable and continuous wind power production. The scale parameter "c" showed that wind power is most spread in August and least spread in November. Seasonal analysis indicated that wind power is more stable and more spread during the wet season.

For the annual and seasonal mean wave power density, the wave power in the 0–5 kW/m category prevailed in the study area. The wind power density (WPD) values varied from 7.66 to 83.44 W/m², which falls within Class I of the wind power classification rating. The wave power density (WVPD) in the 0–5 kW/m category had the highest cumulative frequency in the area but fell below the 6 kW/m relative-rich energy region threshold. Therefore, it is advised that the study area may not be economically viable for bankable energy generation.

Validation analysis revealed near-perfect agreement between buoy (observational) and ERA5 Reanalysis data. Based on the findings, it is recommended that these locations are not economically viable for large-scale wind-wave energy generation. The identified energy potentials may, at best, be adequate for domestic purposes. However, it should not be overlooked that higher bankable energy potentials may exist deeper offshore.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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AUTHOR'S PROFILE

P. A. Enikanselu (PhD) is a Professor of Exploration Geophysics in the Department of Applied Geophysics, Federal University of Technology, Akure, Nigeria. He has been involved in teaching and research of the subject for over thirty-two years. His area of specialisation is Exploration Seismic and Borehole Geophysics. He has authored over forty publications and supervised about twenty-five Postgraduate (M.Tech. & PhD) graduates. His research output has contributed to Hydrocarbon and Groundwater Development in Nigeria. He is a member of the Nigeria Association of Petroleum Explorationists (NAPE) and the current Principal Investigator of the Renewable Energy Research Group of the University. He is a recipient of both the Institution and National Research Grants.

A.A Balogun (PhD) is a Professor and a tenured faculty me the Department of Meteorology and Climate Science at the Federal University of Technology, Akure (FUTA) where he completed a three-year term (2018 -2021) as Chair of the Department. He is also Head, Laboratory for Geoecology and Sustainable Food Systems (GeoLab). Professor Balogun served as Coordinator, Graduate Research Program in West African Climate System (GRP-WACS) of the West African Science Service Center for Climate Change and Adapted Land Use (WASCAL) from August 2014 to August 2015. Professor Balogun is an award-winning climate scientist whose research focused on carbon, water, momentum and energy exchanges in human-modified (urban) landscapes as controlled by land use, climatic, and biophysical processes. These include air pollution studies in rapidly changing mid-latitude urban areas, energy and water cycle processes in sub-Saharan Africa, Europe, the USA and Mexico. Professor Ahmed Balogun is a renowned expert on climate adaptation strategies, resilience and sustainability.

T. Ewetumo (PhD), is a distinguished Associate Professor at the Department of Physics, Federal University of Technology, Akure. He earned his B.Tech., M.Tech., and Ph.D. in Physics from the same institution in 1994, 2002, and 2011, respectively, specializing in Electronics Measurement and Instrumentation. A member of the Nigeria Institute of Physics, Professor Theophilus has attended numerous conferences and workshops, showcasing his commitment to academic excellence. With an impressive 65 publications to his credit, Professor Theophilus has made significant contributions to his field of study. His research expertise and dedication to teaching have earned him recognition as a leading scholar in physics. His academic achievements and professional affiliations underscore his reputation as a respected authority in his field

A. A. Osinowo (PhD), had a Doctor of Philosophy (PhD) and a Doctor of Science (D.SC) in Physical Oceanography in 2017 at Ocean University of China. He had his Master of Technology in Meteorology in 2009 and Bachelor of Technology in Meteorology in 2002, both at the Federal University of Technology Akure. He majored in Physical Oceanography/ Marine Meteorology, particularly on Ocean wave climatology and Renewable Energy. He has 27 publications from peer reviewed journals of which most are from international journals. He is currently a senior lecturer at the School of Earth and Mineral Sciences/Department of Marine Science and Technology, Federal University of Technology Akure, Ondo State, Nigeria. He is a member of the Nigerian Meteorological Society. He is equally a member of the renewable energy research team

M. O. Ogundare (PhD), holds a PhD degree in Earth Sciences. She is a lecturer I in the Department of Marine Science and Technology, Federal University of Technology Akure. Her area of specialization is Marine Biogeochemistry and has been involved in teaching and research in the areas of her research interest of Ocean Acidification and Marine Pollution for over ten years. Her research output has contributed to the understanding of carbon solubility pump in the Southern Ocean, long-time variability of carbon dioxide fluxes in the Tropical Atlantic

Ocean and coastal trace metal pollutions in the Gulf of Guinea. She is a recipient of Pier2Peer scholarship grant award by The Ocean Foundation (TOF) for Global Ocean Acidification Observing Network (GOA-ON) in 2022.

O. R. Ashiru (PhD), is a is a tenured faculty member in the Department of Marine Science and Technology, Federal University of Technology Akure, Nigeria. She has a PhD. in Marine Geology from the University of Chinese Academy of Sciences, Institute of Deep-Sea science and Engineering, Sanya, China under the CAS-TWAS fellowship. Her research focus is Marine Geology with publications is vast topics including Seismic geomorphology, Coastal dynamics and pollution, Coastal Ecology, Seismic and borehole petrophysics etc. She is a member of many relevant associations including AAPG- American association of Petroleum Geologists, IAS- International association of Sedimentologists, ECOP Africa- Early career Ocean Professionals, NMGS- Nigerian Minning and Geosciences Society, COMEG- Council of Minning Engineers and Geoscientists, African Network of Deep-water researchers. She teaches at both graduate and postgraduate level with many students under her supervision.

J. S. Abe (PhD), is a Senior Lecturer in the Department of Applied Geophysics, School of Earth and Mineral Sciences, Federal University of Technology Akure. He specializes in oil and gas research in the areas of petrophysical analysis, seismic interpretation, seismic inversion, rock physics analysis, data mining and amplitude versus offset. He is a member of the renewable energy research team. He has about thirty (30) publications that cut across different areas of oil and gas, mineral and groundwater exploration. He is a member of the Nigerian Association of Petroleum Exploration (NAPE). He has a strong passion for geophysical software development.

A. S. Ifanegan, is an Assistant Lecturer in the Department of Applied Geophysics, School of Earth and Mineral Sciences, Federal University of Technology, Akure. He is an active member of the renewable energy research team and is currently pursuing a PhD in Applied Geophysics. His research interests span reservoir management, enhanced oil recovery (EOR) projects, and renewable energy resource exploration. With a robust background in geophysics and a passion for sustainable energy solutions, he focuses on integrating advanced techniques to optimize reservoir performance and explore environmentally friendly energy alternatives. He has developed applications tailored for enhanced oil recovery projects, with his publications significantly contributing to the understanding of hydrocarbon recovery and renewable energy resource development.

A. Okunlola (PhD), is a distinguished Chief Technologist in the Department of Meteorology and Climate Science at the Federal University of Technology Akure. He attained his Ph.D. in Meteorology and Marine Instrumentation, demonstrating his expertise in this field. With an impressive research portfolio, Dr. Abraham has authored eight journal articles, contributing significantly to the body of knowledge in meteorology and climate science. Since joining the university in 2007, Dr. Abraham has consistently demonstrated his commitment to excellence, providing technical guidance and support to students and faculty alike. His extensive experience, coupled with his academic achievements, makes him a highly respected figure in his department.

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