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Signatures of temperature on radio duct propagation in coastal areas of Nigeria

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सार – मौसम संबंधी परिमाप: पृथ्वी के 950 hPa दाब स्तर पर और 09:00 LT पर तापमान, सापेक्षिक आर्द्रता और दाब, यूरोपीय मध्यम दूरी मौसम पूर्वानुमान केंद्र (ECMWF) के अभिलेखागार से प्राप्त ERA-5 उपग्रह डेटा से प्राप्त किए गए और ITU-R मॉडल का उपयोग करके संशोधित रेडियो अपवर्तकता और प्रवणता का अभिकलन करने के लिए इस्तेमाल किया गया। अभिकलन के नतीजे का इस्तेमाल नाइजीरिया के तटीय इलाकों (क्रॉस रिवर स्टेट में अकपाबुयो, बायेलसा स्टेट में एकेरेमोर, रिवर्स स्टेट में पोर्ट-हारकोर्ट, लागोस स्टेट में बडाग्री और ओंडो स्टेट में इलाजे) में रेडियो डक्ट के तापमान का पता लगाने में किया गया। नतीजों से पता चला कि परिवर्तित रेडियो अपवर्तक प्रवणता, 'M' की उच्च मान आर्द्र ऋतु के महीनों में देखा गया, जिनका औसत मान 102 M-यूनिट/km था और शुष्क ऋतु के महीनों में निम्न मान देखा गया, जिनका औसत मान 87 M-यूनिट/km था। शुष्क ऋतु में डक्टिंग की घटनाएं क्रमशः -13 M-यूनिट/km, -12 M-यूनिट/km, और -5 M-यूनिट/km मान के साथ पाई गईं। नतीजों से पता चलता है कि राज्य में अकपाबुयो, क्रॉस रिवर में संशोधित रेडियो अपवर्तकता और प्रवणता का सबसे मज़बूत मान लगभग 100 M/km है और डक्ट परत में 'M´ का सबसे निम्न मान लगभग -5 M/km है। यह भी देखा गया कि नाइजीरिया में अध्ययन की जगहों पर रेडियो संकेत को ट्रैप करने वाले रेडियो डक्ट 26 °C से ज़्यादा तापमान पर बनते हैं।

ABSTRACT. Meteorological parameters: temperature, relative humidity and pressure at the earth's and 950 hPa pressure level and at 09:00 LT were obtained from ERA-5 satellite data obtained from the archive of European Centre for Medium-Range Weather Forecast (ECMWF) and was used to compute modified radio refractivity and its gradient using ITU-R model. The result of the computation was then employed in deducing the temperature at which radio duct occurs in the coastal areas of Nigeria (Akpabuyo in Cross River State, Ekeremor in Bayelsa State, Port-Harcourt in Rivers State, Badagry in Lagos State and Ilaje in Ondo State). The results showed that high values of modified radio refractivity gradient, M´ were observed during the wet season months with an average value of 102 M-units/km, and low value during the dry season months with an average value of 87 M-units/km. Ducting occurrence were found during the dry months with -13 M-units/km, -12 M-units/km, and -5 M-units/km values respectively. The results show that Akpabuyo, Cross River in state have the strongest value of modified radio refractivity gradients of about 100 M/km and the minimum value of M´ in the duct layer of about -5 M/km. It was also observed that, radio ducts that can trap radio signals in the study locations in Nigeria are formed at temperature of more than 26 ºC.

Key words – Tropospheric ducting, Modified radio refractivity gradient, Coastal area, Temperature.

1. Introduction

Anomalous propagation of radio waves in the atmosphere emanates from the changes in atmospheric radio refractivity with altitude. The changes also result in radio duct conditions. These conditions can be observed with the mean gradient of atmospheric refractive index with height above the ground surface (Sasaki and Akyama, 2014; Saleem, 2015). Within duct layers, the curvature of a propagating wave trajectory becomes smaller than the radius of the earth and consequently, radio signal may get trapped between two levels which often enhance the strength of such wave. Ducting is an anomalous radio propagation in which the waves are bent towards the earth's surface as a result of significant decrease in atmospheric refractivity. It is usually caused by temperature inversion in the troposphere which gives rise to the downward bending of the waves with a curvature higher than that of the earth. Ducting is an abnormal form of refraction which occurs in the troposphere. Its occurrence is determined by the numeric value of radio refractivity gradient at a particular time in a given location. The ducts formation is primarily due to the atmosphere's water vapour content since this has a stronger influence on the index of refraction (refractivity gradient) than temperature gradients do. Due to the inhomogeneity of the troposphere, waves propagated in the troposphere undergo bending, depending on the tropospheric conditions as a result of changes in temperature, pressure and humidity of the environment. Radio energy is then trapped between boundaries or layer in the troposphere and the surface of the earth or sea (surface duct) or between two boundaries in the troposphere (elevated duct) leading to very high signal strengths been obtained at very long distance (beyond line-of-sight) which make the signal strength exceeds its free-space value.

Several studies have been carried out regarding this subject matter, among which are the works of Bech *et al*. (2002); Atkinson and Zhu, (2006); Adediji and Ajewole, (2008); Kwon, *et al*. (2010); Ashidi, *et al*. (2015); Adediji, *et al*. (2015) and Ahmad, *et al*. (2016). Furthermore, most of the works on the subject in Nigeria are on surface radio refractivity which are derived from extrapolated data from radiosonde measurements. Examples include: Willoughby, *et al.* (2002); Falodun and Ajewole, (2006); Okpani, *et al.* (2015); Ojo, *et al.* (2015); Akpootu and Iliyas, (2017); Ojo, *et al.* (2017); Emmanuel *et al.* (2017); Paul and Ayegba, (2018); Emmanuel, (2019); Tanko, *et al.* (2019); and so on. The information on radiosonde measurements lacks the spatial and temporal resolutions which are necessary for the measurement of small-scale variations particularly in the lower atmosphere (Lowry, *et al.* 2002). Furthermore, it is generally recognized that radiosonde measurements do not have a sufficiently high degree of accuracy to be completely acceptable for use in observing changes in the degree of stratification of the very lowest layers of the atmosphere (Hajj, *et al*. (2002).

It has also been reported that ducts are frequently observed in the coastal areas where the horizontal variation of refractive index cannot be ignored (Deshpande, 1974; Rajagopalan and Raghavan, 1980; Chou and Kiang, 2014). Ducting may also affect radio communications links or falsely extend the apparent radar range of a target on or near the sea surface. Ducts occurs when M´ becomes negative and this may force the electromagnetic signal to move within the duct boundaries (Mentes and Kaymaz, 2007). However, not much studies have been carried out on the subject matter in the coastal areas of Nigeria where some human activities like fishing, creation of large amount of chemical wastes, irrigation purposes, gas flaring, and so on are carried out on daily basis. These activities which led to energy transfer occurring at the interface between the water bodies and the ground surface results into turbulence phenomena which can influence the formation of radio ducts.

Ducting is usually caused by temperature inversion in the troposphere which gives rise to the downward bending of the waves with a curvature higher than that of the earth. It is estimated from radio refractivity gradient using ITU Recommendation (ITU-R, 2012). The radio refractive index is a function of air temperature, humidity, atmospheric pressure and water vapour pressure. Thus, in radio propagation studies, the parameter; radio refractivity, N which is related to refractive index, n is often used. Thus, n is related to N as (ITU, 2019);

$$n = 1 + N \times 10^{6} \quad (1)$$

while N is;

$$N = 77.6\frac{P_d}{T} + 72\frac{e}{T} + 3.75 \times 10^{5}\frac{e}{T^{2}} \quad (2)$$

with the dry term, N_{dry} given as:

$$N_{dry} = 77.6\frac{p_d}{T} \quad (3)$$

and N_{wet} as:

$$N_{wet} = 72\frac{e}{T} + 3.75 \times 10^{5}\frac{e}{T^{2}} \quad (4)$$

where P_d is the dry air pressure (hPa), P is the total air pressure (hPa), e is the water vapour pressure (hPa), T is the absolute temperature (K) and

$$P = P_d + e \quad (5a)$$

$$i.e. P_d = P - e \quad (5b)$$

From equation (5b), equation (2) can be written as:

$$N = 77.6\frac{P}{T} - 5.6\frac{e}{T} + 3.75 \times 10^{5}\frac{e}{T^{2}} \quad (6)$$

Equation (6) is approximated with reduced accuracy as:

$$N = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right) \quad (7)$$

The relationship between saturated water vapour pressure, e and relative humidity, H is given by:

$$e = \frac{H.e_s}{100} \quad (8)$$

With

$$e_s = EF.aexp\left[\left(\frac{b-\frac{t}{d}}{t+c}\right).t\right] \quad (9)$$

and

$$EF_{water} = 1 + 10^{-4}[7.2 + P(0.0320 + 5.9 \times 10^{-6}t^{2})] \quad (10a)$$

$$EF_{ice} = 1 + 10^{-4}[2.2 + P(0.0383 + 6.4 \times 10^{-6}t^2)] \quad (10b)$$

where; t is temp (°C), P is total atmospheric pressure (hPa), H is relative humidity (%) e_s is saturated vapour pressure (hPa) at temperature, t (°C), EF is evaporation factor; therefore, EFwater and EF_{ice} are the evaporation factors for water and ice respectively and the constants a, b, c and d are:

For water: a = 6.1121, b = 18. 678, c = 257.14, d = 234. 5 (valid between -40° to +50°) and For ice a = 6.1115, b = 23. 036, c = 279.82, d = 333.7 (valid between -80° to +0°).

The refractivity gradient, $\frac{\Delta N}{\Delta h}$ is given as:

$$N' = \frac{\Delta N}{\Delta h} = \frac{N_s - N_h}{H_s - H_h} \quad (11)$$

where, N_S is the refractivity at surface level, N_h is refractivity at 950 hPa pressure level (H_h) and H_s is the height at the ground surface.

Considering the earth's curvature, the modified refractivity M, is defined as (Bech, et al., 2002); (Falodun *et al*., 2019):

$$M = N + 157h = N + \frac{z}{10^{-6}r_e} \approx N + 0.157z \quad (12)$$

where M is the dimensionless modified radio refractivity (M-unit/km), N is radio refractivity (N-units), r_e is the earths radius (6370 km) and h or z is the altitude (height) in km.

Performing the derivative of equation (12) with respect to height h, the modified refractivity gradient M´ is expressed as (Kwon *et al*., 2010):

$$\acute{M} = \acute{N} + 157 \quad (13)$$

where N´ is refractivity gradient (N-units/km). M´ in the study locations were calculated using equation (13).

2. Data and methodology

For the purpose of this study, ERA-5 satellite data obtained from the archive of European Centre for Medium-Range Weather Forecast (ECMWF) was used. ERA-5 is a dataset showing results of a global climate re-analysis from year 1979 to date. ECMWF has global spatial coverage with a horizontal resolution of about 80 km. The model and analysis (4 DVAR with a 12 hour window) use 60 vertical levels between surface and 6 hours for the upper airfields (Hersbach *et al*., 2020). Four years surface and upper air data spanning January 2015–December 2018 for five locations across Nigeria coastal areas. The data contains daily and monthly records at 09:00 LT of temperature and relative humidity at 950 hPa pressure levels. Modified refractivity and its gradient were then computed from the collected data and their seasonal and annual variations were analyzed. The spatial distributions of modified radio refractivity gradient and temperature were also evaluated.

Nigeria is located within the Equator and the Tropic of Cancer. The climatic condition varies in most parts of the country; in the northern part, the climatic condition is arid, and to the south, there is an equatorial type of climate. The weather condition can be generally characterized into two seasons: Wet season (April to October) and Dry season (November to March) in the succeeding year in most parts of the country. The overall changes in meteorological parameters determine the changes in climate in the country each year.

The coastal zone is an interface between the land and sea, which comprised of a collection of coastal land, intertidal areas aquatic systems including the network of rivers and estuaries, islands, salt marshes, wetlands, and beaches (Cicin-Sain and Knecht, 1998). It is used extensively and increasingly for a large number of activities which includes human settlement, agriculture, trade, industry and amenity and so on. The prevalence of sea and land breezes which play a major role in the development and intensification of weather events in the coastal zones account for the high concentration of water vapour. This study is being carried out in the Nigerian coastal areas because of the constantly changing weather conditions and are hence prone to abnormal propagation conditions, such as atmospheric radio ducts (Mufti, 2011). The study locations are: Akpabuyo in Cross River State, Ekeremor in Bayelsa State, Port-Harcourt in Rivers State, Badagry in Lagos State and Ilaje in Ondo State (Fig. 1). Akpabuyo is a Local Government Area of Cross River State in Nigeria with a population of 271,395 at the 2006 census. Ekeremor is one of the eight Local Government Area in Bayelsa State. It borders Delta State and has a coastline of approximately 60 km on the Bight of Bonny. with a population of 270,257 at the 2006 census. Port-Harcourt is the capital and the largest city in Rivers State, Nigeria. It lies along the Bonny River and is located in the Niger Delta. As at 2006, Port-Harcourt has an estimated population of 1,865,000. Badagry is a coastal town and Local Government Area in Lagos State, Nigeria. It is between the city of Lagos and share a border with the Republic of Benin. It is situated on the Southwest coast of Nigeria, bordered by the Gulf of Guinea to the South, It

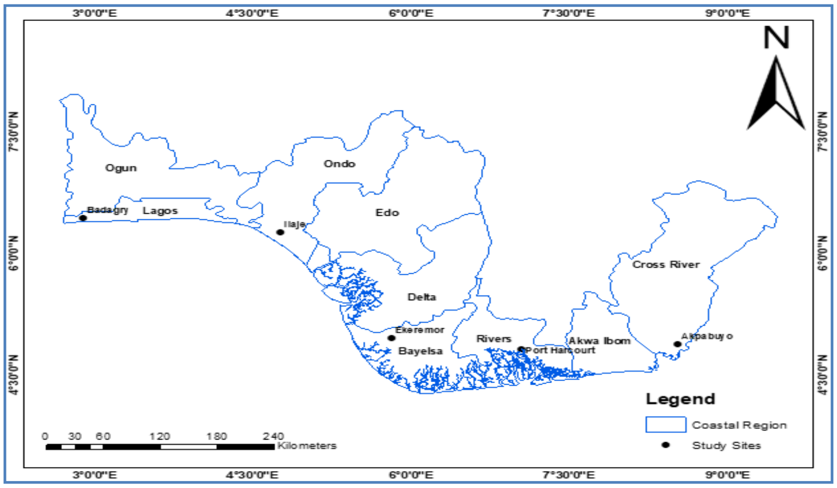

Fig. 1. Geographic map of the research stations

TABLE 1

Parameters of the Research Stations

S/N	Locations	Coordinates Lat. (°N)	Coordinates Long. (°E)	Elevation (m)	Area (km^2)
1	Akpabuyo, Cross River	4.88	8.53	108	1,241
2	Ekeremor, Bayelsa	4.95	5.81	9	1,810
3	Port-Harcourt, Rivers	4.82	7.05	27	369
4	Badagry, Lagos	6.43	2.89	8	441
5	Ilaje, Ondo	6.26	4.77	0	1,318

has a population of 241,093 according to 2006 census. Ilaje is a Local Government Area in Ondo State, Southwest, Nigeria. It has a population of 290,615 at the 2006 census. Table 1 gives the geographic coordinates, elevation and area covered by the study locations, while Fig. 1 shows the map of the locations in Nigeria.

3. Results and discussion

3.1. *Seasonal variation of modified radio refractivity (M)*

The values of M have been determined using equations (7) to (9) and (12). Fig. 2 presents the seasonal mean values of M across the study locations. It was deduced that M decreases from November to December while it increases from January to March over the study locations. A dip in M was noticed during the month of April across all the study locations except at Ekeremor that shows no variability. A gradual decrease in M occurred from May to August across all the study locations and a further rise in values up to November. Similar trends of pattern were observed in Akpabuyo, Badagry, Ekeremor and Port Harcourt. These can be attributed to variability in the weather conditions of the troposphere in these locations.

Furthermore, a high mean value of 281 M-units was obtained in Akpabuyo in March (dry season). The physical phenomenon responsible for the reduction in value in August can be attributed to the occurrence of slight drought called 'August-break' during the rainy season in this rain forest zone of Nigeria. The break usually lasted for about 2-3 weeks during which water vapour pressure at the surface is minimum. Its occurrence is in association with the Inter Tropical Discontinuity (ITD) reaching its northern-most position and consequently retreating southward, and this gradually leads to the end of the rainy season in October. A notable observation is that all locations exhibit a clear distinction between the wet and dry seasons, with higher values observed during the wet season than during the dry season. The transition from the dry to wet season in March-April is characterized by a rapid increase in values for all locations, while the transition from the wet to dry season in October-November is marked by a gradual decrease, with a sharp drop in December. The wet season is characterized by more stable values with minor fluctuations, whereas the dry season exhibits more dramatic changes, particularly the sharp decline in December-January and the rapid rise in February-March.

These trends implies that modified radio refractivity in these locations is strongly influenced by seasonal weather patterns, likely related to changes in humidity, temperature and atmospheric pressure.

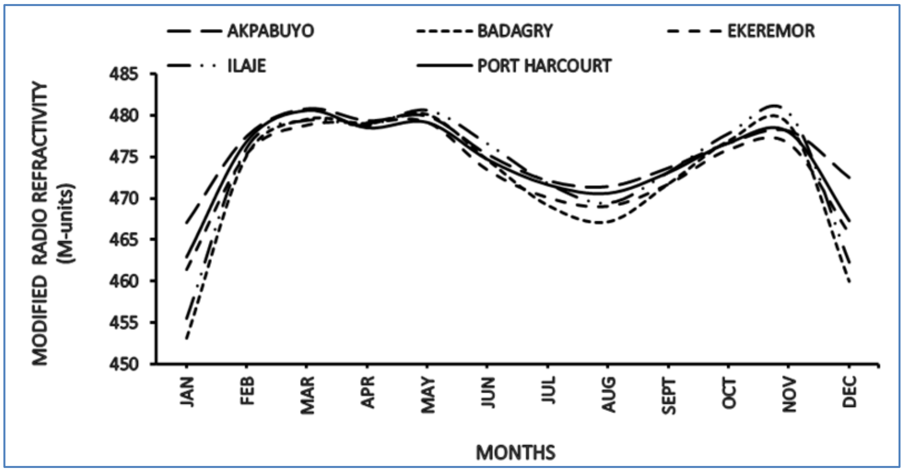

Fig. 2. Seasonal mean value of modified radio refractivity, M at 950 hPa

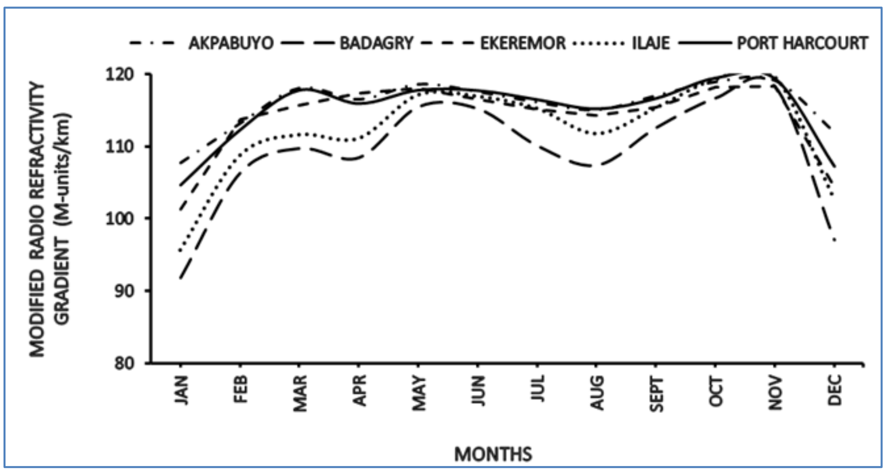

Fig. 3. Seasonal mean of modified radio refractivity gradients, M´ at 950 hPa

3.2. *Seasonal variation of modified radio refractivity gradient (M')*

The values of the modified radio refractivity gradients M´ were obtained using equations (11) and (13). Fig. 3 depicts the seasonal mean values of M´ for the study locations. During the wet season, M' values generally show a decreasing trend for all the locations. This indicates a lower refractivity gradient, which means the atmosphere is less refractive during the wet period. During the dry season, M' values show an increasing trend for most locations. This suggests a higher refractivity gradient, meaning the atmosphere is more refractive during the dry period. All the locations exhibit similar seasonal patterns in M', but with some variations in magnitude of the changes. For instance, Akpabuyo, Badagry, and Ekeremor gave the highest M' values, indicating a more refractive atmosphere in these locations. Ilaje and Port Harcourt show relatively lower M' values, suggesting a less refractive atmosphere in these locations. The differences in M' between the locations may be due to factors such as terrain, climate and local environmental conditions.

These results show that average values of M´ during the wet season is about 115 M/km, and average value of 110 M/km during the dry season. The high values of M´and its variation is in consonance with the work of Ayantunji *et al.*, *(*2011) for Coastal areas. Table 2 show that M´ for the wet season were higher than the dry season.

3.3. *Annual variation of modified radio refractivity (M)*

Fig. 4 shows the annual variation of the mean values of M at 950 hPa in the study locations. The results show that the values of M increase steadily from year 2015 to 2017 and dropped in 2018 across all the study locations, except in Ilaje that showed increase up to 2018. No

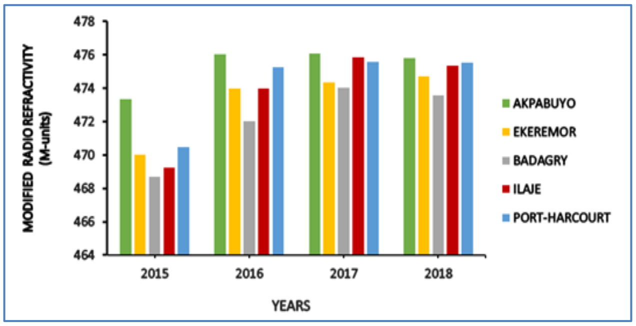

Fig. 4. Annual mean values of modified radio refractivity, M at 950 hPa

TABLE 2

Average Monthly Value of M

S/N	Locations	Average value of M´ (M-units/km)	
		wet season months	Dry season months
1.	Akpabuyo, Cross River	117	114
2.	Ekeremor, Bayelsa	116	111
3.	Badagry, Lagos	112	105
4.	Ilaje, Ondo	115	108
5.	Port Harcourt, Rivers	117	112

significant variation observed in the values of M at Akpabuyo, Port Harcourt and Ekeremor from year 2016 to 2018, while the value increases at Badagry from year 2016 to 2017. Furthermore, slight decrease in the values of M was also observed at Badagry and Ilaje from year 2017 to 2018. The relative differences in the values of M across the locations also remain consistent, indicating that local factors may contribute to the variations in refractivity which also indicates that the annual fluctuations in M values suggest the presence of seasonal variations in the atmospheric conditions.

3.4 *Annual variation of modified radio refractivity gradient (**M´**)*

Fig. 5 shows the annual mean values of M´ at 950 hPa across the study locations. In Akpabuyo, the value of M´ shows a relatively consistent trend over the years, with values oscillating around 112 M-units/km. M´ values in Badagry display a slight increase trend from 2015 to 2018, with values ranging from around 108 M-units/km to 112 M-units/km. The variation in the value was more pronounced at Ilaje, with a decrease from 2015 to 2016, followed by an increase in 2017 and 2018. The annual mean of M´ values for Port-Harcourt demonstrates the most significant variation, with a decrease from 2015 to 2016, followed by a sharp increase in 2017 and a decrease again in 2018.

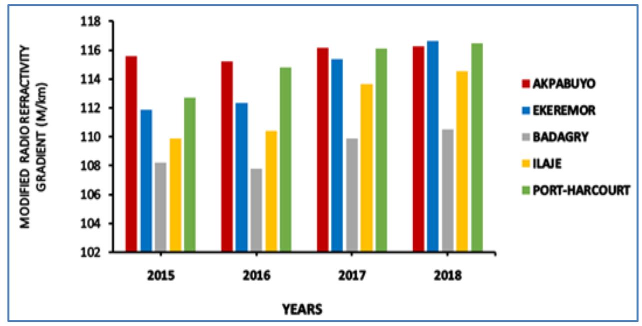

Fig. 5. Annual mean values of modified radio refractivity gradients, M´ at 950 hPa

The high values observed are due to high humidity in the selected Nigeria Coastal Areas which are under the influence of high moisture-laden maritime air which result from continuous migration of inter-tropical discontinuity with the sun. However, the slight annual difference may be due to the erratic nature of the ocean waves over the region (Akpootu and IIiyasu, 2017). The implication of the results is that radio propagation conditions across the locations have varying degree of occurrence with super-refractive conditions more prevalent.

3.5. *Seasonal variation of modified radio refractivity, M with temperature*

Figs. 6(a-e) shows the seasonal variation of M with temperature (Celsius) across the study locations from 2015 to 2018. The values of M increases with temperature from January to March over the study locations, which shows that a radio duct can occur at higher temperatures than at lower temperatures (Kwon *et al*. 2010). However, in all the locations, the values of M decrease from the month of April to August (wet season months), rise in November and finally drop in December. During the wet season, the M-values fluctuate significantly, showing a saw-tooth pattern with alternating peaks and troughs. The M values range from around 465 M-units to 480 M-units, with the highest peak occurring in July. The temperature values also show a similar fluctuating pattern, with the mean highest temperature of about 23°C in May and the mean lowest temperayture of about 21°C in August. The M and temperature values appear to be inversely related, with the M peaks generally corresponding to the temperature dips, and vice versa. During the dry season (November to March), the M values exhibit a more gradual and relatively smooth decline, dropping from around 475 M-units in November to around 465 M-units in March. The temperature values show a steady decrease during the dry season, dropping from around 22°C in November to around 21°C in March. These results are consistent with the work of Akpootu and IIiyasu (2017).

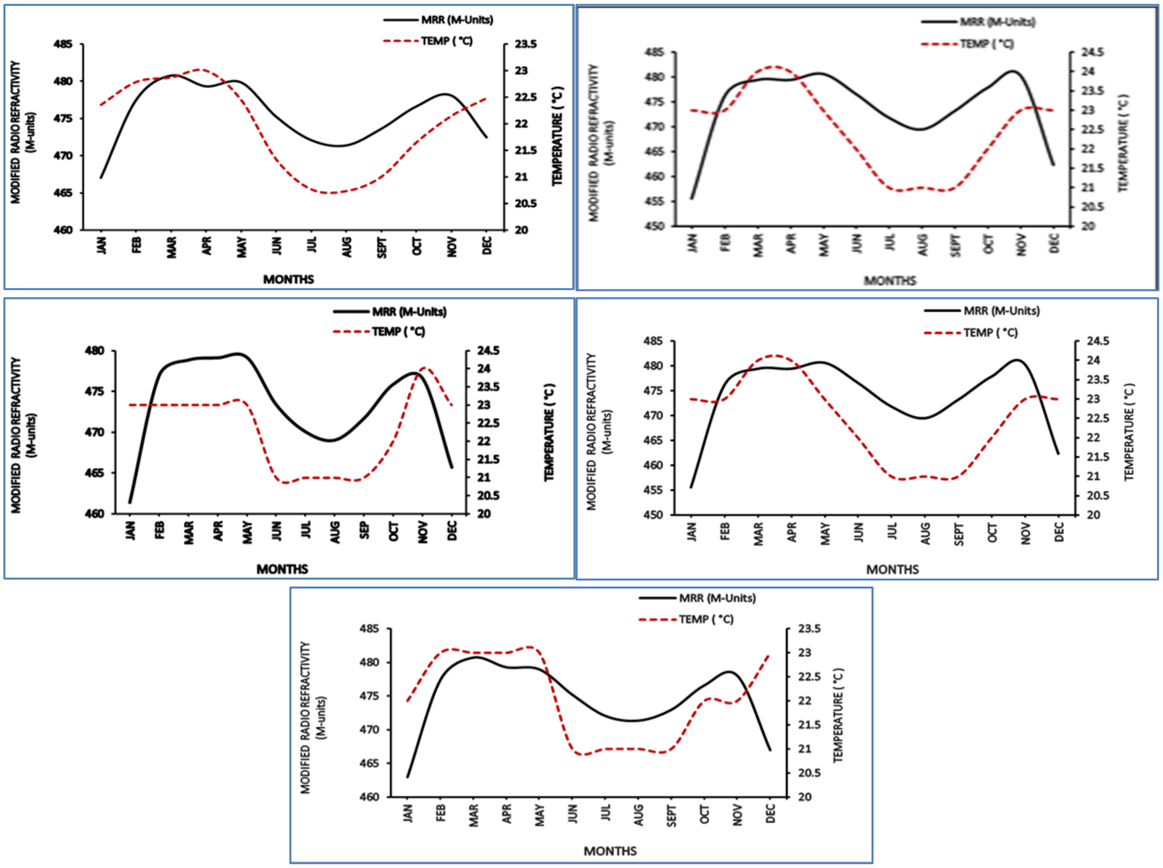

Fig. 6(a-e). Seasonal Variation of Modified Radio Refractivity with Temperature from 2015 to 2018 over: (a) Akpabuyo, (b) Badagry, (c) Ekeremor, (d) Ilaje and (e) Port Harcourt

TABLE 3

Seasonal Mean Distribution of Duct at 09:00 LT

Months	Mod. rad. refractivity gradients in duct layer	Temperature (°C)
Jan.	-12	26
Feb.	-5	26
Dec.	-13	27

3.6. *Monthly Distribution of Duct*

Trapping or ducting occurs when M´ becomes negative (Mentes and Kaymaz, 2007). Table 3 summarizes the monthly distribution of duct and the temperature at which duct occurred during 09:00 hr. LT over the study locations. Duct occurrence were found in January, February & December and the highest temperature value were found in December with an average of 27 °C having the minimum value of M´ in the duct layer. These results also showed that high temperature values occurred during the dry season and radio ducts in the coastal areas of Nigeria are formed at temperature of more than 26 °C. Since the meteorological characteristics differ from region to region or country to country, it is estimated that the temperature at which radio signals are trapped will vary across regions of the world.

3.7. *Spatial distributions of modified radio refractivity gradient and temperature in the study locations*

Figs. 7 and 8 gives the spatial distributions of M´ and temperature over the study locations during 09:00 hr LT at 950 hPa pressure level. The modified radio refractivity gradient ranges from 110 to over 116 M-units/km across the locations. It can be seen that Akpabuyo in Cross River state recorded the highest value of 100 M/km with the lowest temperature value of 26 °C while Badagry in Lagos state have the minimum value of about 91 M-units/km and highest temperature value of 28 °C. The implications are that Akpabuyo, with higher gradients may experience more radio ducting or trapping effects while Badagry with lower gradients might have more standard radio propagation effects. The map is crucial for planning radio communication systems across

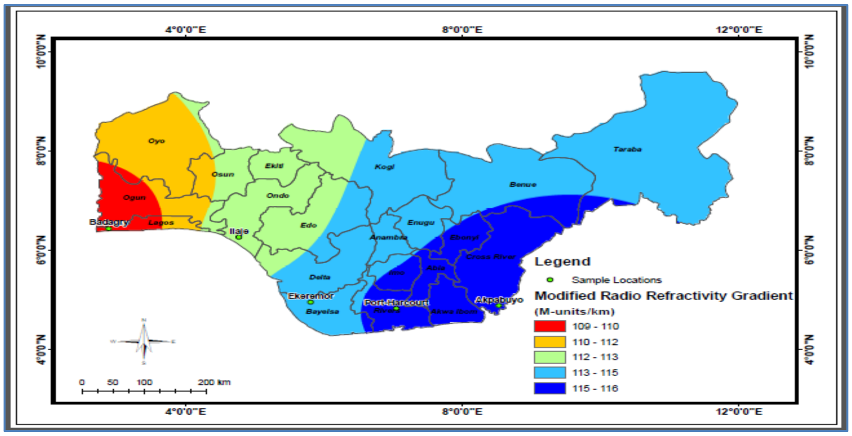

Fig. 7. Spatial Distribution of M´ over the Study Locations

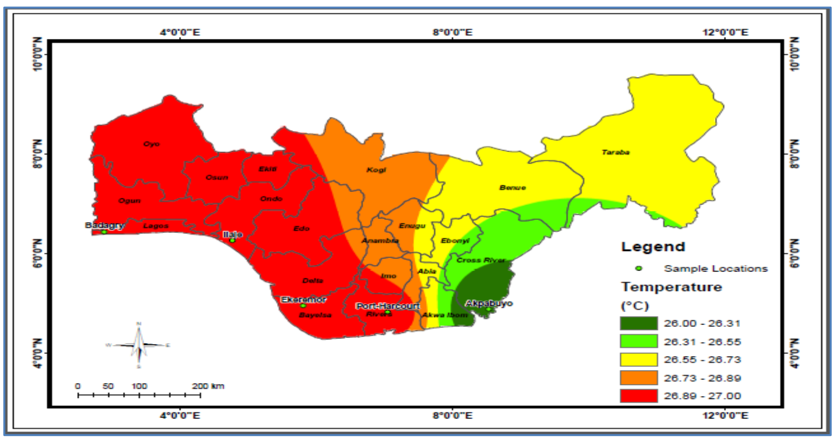

Fig. 8. Spatial Distribution of Temperature over the Study Locations

TABLE 4

Summary of Mean Modified Radio Refractivity and Modified Radio Refractivity Gradient with Temperature Over the Study Locations

S/N	Locations	Mod. Radio Refractivity (M-units)	Mod. Radio Refractivity Gradient (M-units/km)	Mod. Radio Refractivity Gradient in duct layer (M-units/km)	Temp. (°C)
1.	Akpabuyo	475	116	-4	26
2.	Ekeremor	473	114	-9	27
3.	Badagry	472	109	-20	27
4.	Ilaje	474	112	-5	27
5.	Port-Harcourt	474	115	-5	27

the coastal areas of Nigeria which can help predict areas where anomalous propagation might be experienced more frequently. Furthermore, the spatial distribution of modified radio refractivity gradient provides a comprehensive view of how radio propagation conditions vary across the study area, highlighting the importance of considering local atmospheric conditions in radio communication planning and meteorological studies. The spatial distribution of temperature across the locations (Fig. 8) shows temperatures ranging from 26 °C to 27 °C and can provide useful information for understanding the climatic conditions of the coastal areas with its potential impacts on various sectors such as agriculture, energy, radio propagation planning and so on. Factors such as proximity to the coast, elevation differences across the areas and large-scale atmospheric patterns could contribute to these temperature variations. This temperature distribution indicates that locations with higher temperatures generally show lower refractivity gradients, and vice versa. Furthermore, Table 4 gives the summary of some radio parameters with temperature over the study locations which also indicated that the maximum temperature occurred in Badagry. These results are in agreement with the work of Falodun *et al.*, (2019).

4. Conclusions

The study presented the result of the computation of modified radio refractivity and its gradient using ITU-R model. The result of the computation was employed in deducing the temperature at which radio duct occur in the major five coastal areas of Nigeria. However, the main findings are as follows:

- Ducting occurrence were deduced in the dry season periods (December, January and February).
- The maximum value of the modified radio refractivity gradient occurred at Akpabuyo in Cross River State of about 116 M-units/km
- The minimum value of modified radio refractivity gradient occurred at Badagry in Lagos State of about 109 M-units/km.
- The seasonal patterns in the modified radio refractivity gradient suggest that radio wave propagation conditions in these Nigerian locations are strongly influenced by changes in atmospheric conditions, such as; humidity, temperature, and atmospheric pressure, throughout the year.
- The modified radio refractivity gradient values during the wet season are higher than during the dry season.
- High-temperature values occurred during the dry season months and ducts that can cause trapping of radio signals in the coastal areas of Nigeria are formed at temperatures of more than 26°C.

Hence, radio signal propagated during these occurrences will traverse longer distance beyond the line-of-sight limits; which can cause interference to adjacent stations in terrestrial radio systems. The findings have important implications for planning and optimizing radio communication systems in the region.

Recommendations

As communication networks are growing in the country, it is required that more research work would be carried out using appropriate data and parameters for proper planning of effective communication networks for the nation. Hence, future research work shall focus on comparing satellite data with data from in-situ measurements obtained from other receiving systems over the study locations in order to ascertain accuracy in the information on tropospheric ducting. Also, the same study shall be conducted over other climatic conditions in Nigeria so as to have a fuller database for the prediction of microwave impairment in Nigeria as a whole.

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Authors' contributions

A. T. Adediji: Conception and design of the study and provision of data, revision of the manuscript.
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