Effects of Temperature on Radio Duct Propagation in Selected Coastal Areas of Nigeria

A. T. Adediji[1] and A. P. Iwaotan[2,*]

[1] Department of Physics, Federal University of Technology, Akure, Nigeria
[2] Department of Science Laboratory Technology, University of Medical Sciences, Ondo, Ondo City, Nigeria
*Corresponding author email: iakinwunmi@unimed.edu.ng

Abstract
Meteorological parameters of air temperature, relative humidity, and atmospheric pressure at the ground surface and 950 hPa pressure level at 09:00 LT obtained from the archive of European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis ERA-Interim were used to compute modified radio refractivity and its gradient using ITU-R model. The results of the computation were used to deduce the temperature at which radio duct occurs in the selected coastal areas of Nigeria. The selected locations are Akpabuyo (4.88 ^0N, 8.53 ^0E), Ekeremor (4.95 ^0N, 5.81 ^0E), Port Harcourt (4.82 ^0N, 7.05 ^0E), Badagry (6.43 ^0N, 2.89 ^0E) and Ilaje, (6.26 ^0N, 4.77 ^0E). The results show a similar overall pattern throughout the year in all the locations. Port Harcourt and Badagry often show the highest values while Akpabuyo frequently exhibits the lowest. The results as well show that the modified radio refractivity gradient, M′-values are highest during the wet season (April - October) with an average value of 117 M-$units/km$ at Port Harcourt and Akpabuyo respectively, and lowest during the dry season (November - March) with an average of 105 M-$units/km$ at Badagry. Ducting occurrences were found during the dry months of December, January, and February with -13 M-$units/km$, -12 M-$units/km$ and -5 M-$units/km$ values at Port Harcourt respectively. It was also observed that; radio ducts that can trap radio signals in Nigeria's coastal areas are formed at 26^0C or more.

Keywords: Ducting, modified radio refractivity gradient, temperature, coastal area.

1 Introduction

Anomalous propagation of radio waves in the atmosphere emanates from the changes in atmospheric refractivity with height. The change in atmospheric refractivity also results in duct conditions. These conditions can be investigated with the average gradient of the atmospheric refractive index with height above the earth's surface [12, 13]. Within duct layers, the radius of curvature of a propagating wave trajectory becomes smaller than the radius of the earth, and signal may get trapped between two levels which often enhances the strength of such wave. Research has been carried out in the coastal areas regarding this subject matter. Among such studies are the works of [1, 2, 4 - 7, 9].

Ducting may also affect radio communications links or falsely extend the apparent radar range of a target on or near the sea surface. It was also reported that ducts occur when the modified radio refractivity gradient **M′** becomes negative, which may force the electromagnetic signal to move within the duct boundaries [10]).

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However, not many studies have been carried out on this subject in the coastal areas of Nigeria which comprise some human activities like the creation of large amounts of chemical wastes, irrigation purposes, gas flaring, etc., which may influence the formation of radio ducts thus leading to anomalous radio propagation. Hence the need for this study.

Some specific challenges associated with temperature effects on radio duct propagation in Nigeria's coastal areas include:

Unpredictable signal fades: The changing atmospheric conditions and temperature gradients can lead to unpredictable signal fades, making it challenging to design reliable communication systems. To mitigate these challenges, it is essential to understand the effects of temperature on radio duct propagation in Nigeria's coastal areas and develop adaptive communication systems that can adapt to these unique conditions.

The purpose of this work is to compute modified radio refractivity and its gradient, to deduce spatial distributions of modified radio refractivity gradient with temperature, and to determine the temperature at which ducts can trap radio signals over Nigeria's selected coastal areas.

1.1 Theory

Ducting is an anomalous mode of propagation of radio waves in which the waves are bent towards the earth's surface hence, a significant decrease in atmospheric refractivity. It's usually caused by a temperature inversion in the tropospheric region of the atmosphere, which results in the downward bending of the waves with a curvature greater than that of the earth. Radio energy is trapped between a boundary or layer in the troposphere and the earth's surface or sea (surface duct) or between two boundaries in the troposphere (elevated duct).

The atmospheric radio refractive index is a function of air temperature, humidity, atmospheric pressure, and water vapor pressure. Thus, in radio propagation studies, the parameter; radio refractivity N is related to refractive index, n is often used. The relationship between n and N using [11]:

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

While the radio refractivity, *N* (in N-units) is approximated with reduced accuracy as:

$$N = N_{dry} + N_{wet} = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right) \quad (2)$$

P is the total atmospheric pressure (hPa), e is the water vapor pressure (hPa), T is the absolute temperature (K) and the relationship between saturated water vapor pressure, e, and relative humidity, RH is given by:

$$e = \frac{RH.e_s}{100} \quad (3)$$

$$RH = \frac{100 \times e}{e_s} \quad (4)$$

$$e_s = EF \cdot a \cdot exp\left[\frac{\left(b - \frac{t}{d}\right) \cdot t}{t + c}\right] \quad (5)$$

where EF is the evaporation factor and:

$$EF_{water} = 1 + 10^{-4}[7.2 + P(0.00320 + 5.9 \times 10^{-7} \cdot t^2)] \quad (6a)$$

$$EF_{ice} = 1 + 10^{-4}[2.2 + P(0.00382 + 6.4 \times 10^{-7} \cdot t^2)] \quad (6b)$$

where t is temp (°C), RH is relative humidity (%), e_s is saturated vapour pressure (hPa) at temperature t (°C) and the coefficients 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 radio refractivity gradient, $N^{'}$ (in N-units/km) is given as:

$$N^{'} = \frac{\Delta \mathrm{N}}{\Delta \mathrm{h}} = \frac{N_s - N_h}{H_s - H_h} \quad (7)$$

where N_S is the radio refractivity at the surface level, N_h is radio refractivity at 950 hPa pressure level (H_h), and H_s is the height of 100 m at the surface level.

The modified radio refractivity M, is defined as [7, 8]:

$$M = N + 157h = N + \frac{z}{10^{-6} r_e} \approx N + 0.157z \quad (8)$$

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

Performing the derivative of equation (8) with respect to height h, the modified radio refractivity gradient M′ is expressed as [9]:

$$M^{'} = N^{'} + 157 \quad (9)$$

The value of M′ over the study locations were calculated using equation (9).

2 Data and Methodology

Four years of surface and upper air data spanning January 1st, 2015 December 31st, 2018 used for this work were obtained from the archive of European Centre for Medium-Range Weather Forecast (ECMWF) Re-analysis ERA-Interim at a spatial resolution of 0.25° × 0.25° for five locations across Nigeria coastal areas. The data contains daily and monthly records at 09:00 LT of atmospheric temperature and relative humidity at 950 hPa pressure levels with the coordinates of each location. Modified radio refractivity and its gradient with height at 100 meters were computed, and their seasonal and annual variations were analyzed. Table 1 shows the study locations, the coordinates, the height, and the area covered, while Figure 1 shows the map of the study locations in Nigeria.

Table 1: Characteristics of the study locations

S/N	Locations	Coordinates		Height (m))	Area (km^2)
		Lat. (^oN)	Long. (^oE)		
1.	Akpabuyo	4.88	8.53	108	1,241
2.	Ekeremor	4.95	5.81	9	1,810
3.	Port Harcourt	4.82	7.05	27	369
4.	Badagry	6.43	2.89	8	441
5.	Ilaje,	6.26	4.77	0	1,318

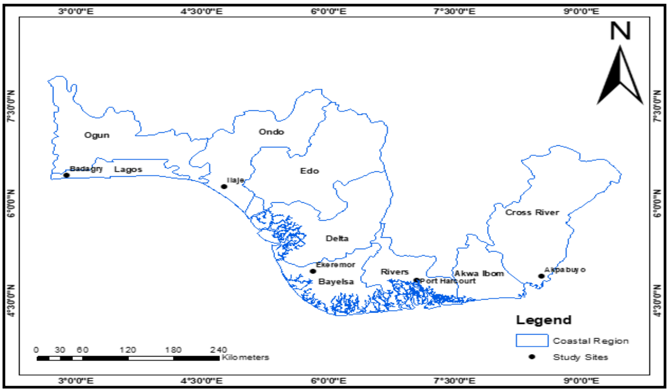

Fig. 1. Geographic map of the study locations. (Source: ArcMap 10.8)

3 Results and Discussion

3.1 Seasonal Variation of Modified Radio Refractivity Gradient (M′)

The values of the modified radio refractivity gradient (M')were obtained using equations (7) and (9). Figure 2 depicts the seasonal mean values of M´ for the study locations.

During the wet season, the 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, the 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. The different locations exhibit similar seasonal patterns in M', but with some variations in the magnitude of the changes. Akpabuyo, Badagry, and Ekeremor stand out with the highest M' values, indicating a more refractive atmosphere in these areas. Ilaje and Port Harcourt show relatively lower M' values, suggesting a less refractive atmosphere in these locations.

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. These findings have important implications for planning and optimizing radio communications systems in the region. Table 2 shows that the values of M′ for the wet season months were higher than values in the dry season months [8].

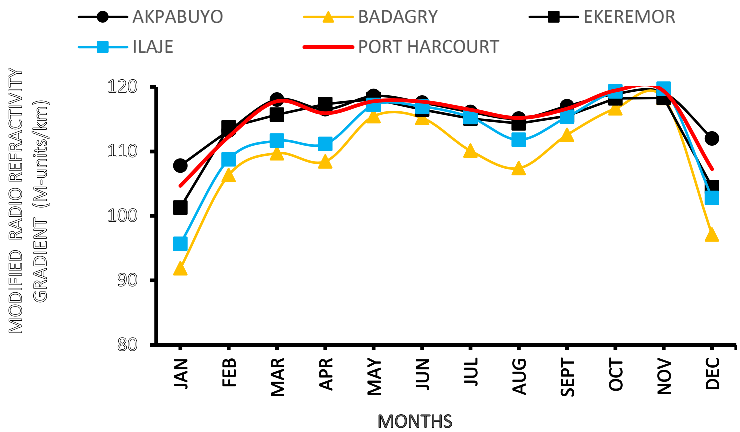

Fig. 2. Mean seasonal values of modified radio refractivity gradients, M′ at 950 hPa

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	117	114
2.	Ekeremor	116	111
3.	Badagry	112	105
4.	Ilaje	115	108
5.	Port Harcourt	117	112

3.2 Annual Variation of Modified Radio Refractivity Gradient (M′)

Figure 3 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 for 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.

Overall, Figure 5 suggests that the annual seasonal variation in the modified radio refractivity gradient is present across the different locations, with Akpabuyo exhibiting more consistent trends, while Port Harcourt shows more pronounced fluctuations from year to year.

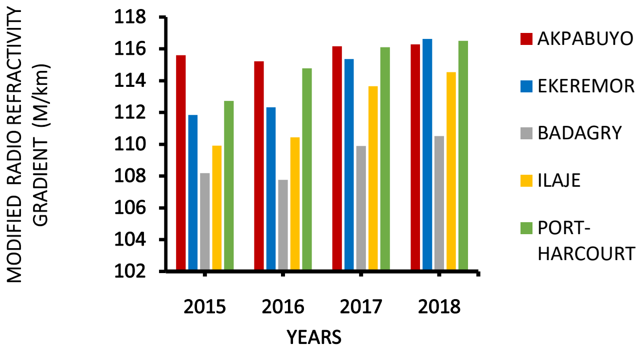

Fig. 3. Annual mean values of modified radio refractivity gradients, M′ at 950 hPa

3.3 Seasonal Variation of Modified Radio Refractivity, M with Temperature

Fig. 4 to 8 shows the seasonal variation of M with temperature (Celsius) for all the study locations from 2015 to 2018.

During the wet season, the M-values fluctuate significantly, showing a saw-tooth pattern with alternating peaks and troughs. The 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 highest temperature reaching around 23°C in May and the lowest around 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 wet 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.

Overall, Figure 4 suggests that the M values are closely linked to the temperature variations, with the wet season showing more pronounced fluctuations and an inverse relationship, while the dry season exhibits a more direct and gradual relationship between the two parameters. These results are consistent with the work of [3].

In Figure 5, during the wet season, the M values exhibit a fluctuating pattern, with peaks and troughs. The temperature values also show a similar fluctuating pattern, with peaks and troughs, but temperature changes are less pronounced compared to the M. Generally, there is an inverse relationship between M and temperature during the wet season. When the temperature increases, the M tends to decrease, and vice versa. During the dry season, the M values show a more stable and consistent trend, with a gradual decrease from November to March. The temperature values also exhibit a more stable trend during the dry season, with a gradual decrease from November to March. The relationship between M and temperature is more direct during the dry season, where both parameters decrease concurrently.

Overall, the relationship between M and temperature appears to be more complex during the wet season, with an inverse relationship, while during the dry season, the relationship is more direct, with both parameters decreasing together. The seasonal variation in the atmospheric conditions, such as moisture content and air pressure, can contribute to the observed patterns in the M and temperature relationship.

In Figure 6, during the wet season, the M and temperature values exhibit a fluctuating pattern, with peaks and troughs. There is a strong inverse relationship between M and temperature during the wet season. When the temperature increases, the M tends to decrease, and vice versa. During the dry season, the M values show a more stable and consistent decreasing trend from November to March. The temperature values also exhibit a decreasing trend during the dry season, though the changes are less pronounced compared to the M. The relationship between M and temperature is more direct during the dry season, where both variables decrease concurrently.

The contrasting trends observed between the wet and dry seasons can be attributed to the differences in atmospheric conditions, such as moisture content, air pressure, and other meteorological factors that influence the modified radio refractivity and temperature. In the wet season, the fluctuations in temperature may be more closely linked to changes in moisture or other environmental factors, leading to the inverse relationship with M. In the dry season, the more stable and direct relationship suggests that the variables are influenced by similar underlying factors, such as decreasing air pressure or humidity.

Overall, the seasonal variation plays a significant role in shaping the relationship between M and temperature, highlighting the importance of considering the environmental context when analyzing these meteorological parameters.

In Figure 7, during the wet season, the M values generally show an increasing trend, reaching their peak around July-August. The temperature values also exhibit a similar increasing trend during the wet season, peaking around the same time as the M. This suggests that during the wet season, the increase in temperature is accompanied by an increase in the modified radio refractivity, which is influenced by factors like humidity and atmospheric conditions. In the dry season, the M values show a decreasing trend, reaching their lowest point around January-February. The temperature values also exhibit a decreasing trend during the dry season, following a similar pattern to the M. This indicates that during the dry season, the decrease in temperature is accompanied by a decrease in the modified radio refractivity, likely due to the drier atmospheric conditions.

Overall, Figure 7 demonstrates a strong correlation between the seasonal variations in temperature and the modified radio refractivity. The peaks and troughs in both parameters align, suggesting that temperature is a significant factor influencing the modified radio refractivity, particularly in relation to the wet and dry seasons.

In Figure 8, during wet season, the M values show a general decreasing trend, indicating lower refractivity. The temperature values also show a decreasing trend, reaching the lowest point around July-August. In the dry season, the M values show an increasing trend, indicating higher refractivity. The temperature values also show an increasing trend, reaching the highest point around May.

Overall, there is an inverse relationship between M and temperature. When temperature is higher during the dry season, the M values are also higher, indicating higher refractivity. Conversely, when temperature is lower during the wet season, the M values are also lower, indicating lower refractivity. This inverse relationship is consistent with the fact that higher temperatures generally lead to lower air density, which in turn results in lower refractivity.

In summary, Figure 8 shows a clear seasonal variation in both M and temperature, with the wet season experiencing lower values and the dry season experiencing higher values. The inverse relationship between M and temperature is also evident, demonstrating the influence of temperature on the modified radio refractivity.

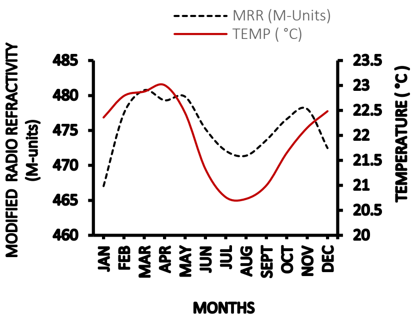

Fig. 4. Seasonal variation of modified radio refractivity with temperature over Akpabuyo from 2015 to 2018

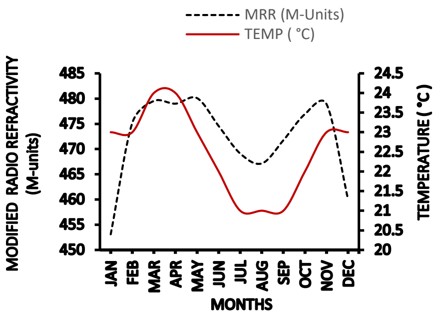

Fig. 5. Seasonal variation of modified radio refractivity with temperature over Badagry from 2015 to 2018

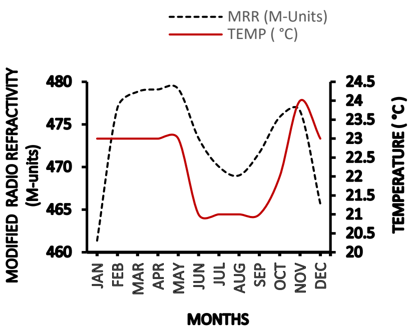

Fig. 6. Seasonal variation of modified radio refractivity with temperature over Ekeremor from 2015 to 2018

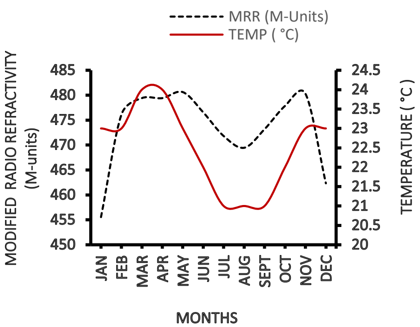

Fig. 7. Seasonal variation of modified radio refractivity with temperature over Ilaje from 2015 to 2018

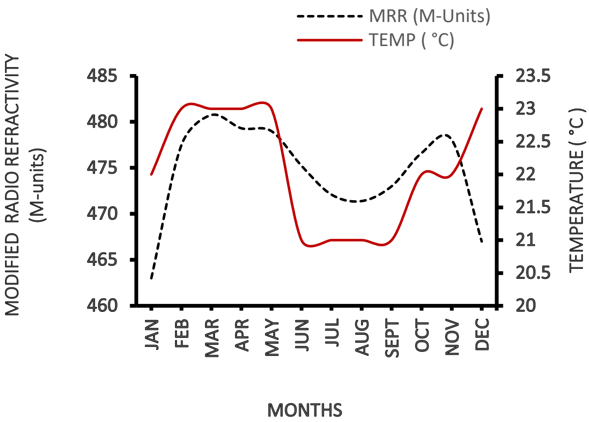

Fig. 8. Seasonal variation of modified radio refractivity with temperature over Port Harcourt from 2015 to 2018

3.4 Seasonal Distribution of Duct

Trapping or ducting occurs when the modified radio refractivity gradient becomes negative [10]. Table 3 summarizes the seasonal distribution of ducts and the temperature at which duct occurred during 09:00 LT in the study locations. Duct occurrences were found in January, February and December at Port Harcourt. The highest temperature values were found during December with an average value of 27°C with the least modified radio refractivity gradient in the duct layer. These results also show that a high temperature occurs during the dry season months, and radio ducts in the coastal areas of Nigeria are formed at 26°C or more.

Since the meteorological characteristics differ from region to region or country to country, it is estimated that the temperature at which radio wave signals are trapped will vary across world regions.

Table 3: Seasonal mean distribution of duct at 09:00 LT

Months	Mod. rad. refractivity gradients in duct layer (*M-units/km*)	Temperature (℃)
Jan.	−12	26
Feb.	−5	26
Dec.	−13	27

Figure 9 shows the spatial distributions of M' over the study locations during 09:00 LT at 950 hPa pressure level, ranging from 110 to over 116 M-units/km. A clear west-to-east transition from higher to lower gradient values was observed, which suggests a systematic change in atmospheric conditions across the locations.

Applications:

- This map is crucial for planning radio communication systems across the coastal areas of Nigeria.
- It can help predict areas where anomalous propagation might occur more frequently.
- The information is valuable for meteorological studies and understanding regional atmospheric dynamics.

This spatial distribution of modified radio refractivity gradient provides a comprehensive view of how radio wave propagation conditions vary across the study area, highlighting the importance of considering local atmospheric conditions in radio communication planning and meteorological studies.

Figure 10 shows spatial distribution of temperature across the locations. The map shows temperatures ranging from 26°C to 27°C across the study locations. Factors such as proximity to the coast, elevation differences across the areas and large-scale atmospheric patterns could contribute to temperature variations. Akpabuyo show the lowest temperature possibly due to maritime influence.

This spatial distribution of temperature provides valuable information for understanding the coastal climate patterns, potential impacts on various sectors such as agriculture, energy, etc., and its relationship with other atmospheric phenomena like radio wave propagation.

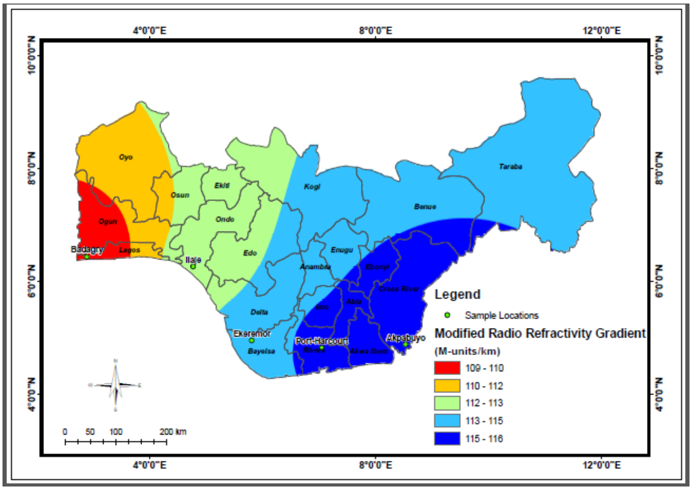

Fig. 9. Spatial distribution of modified radio refractivity gradient. (Source: ArcMap 10.8)

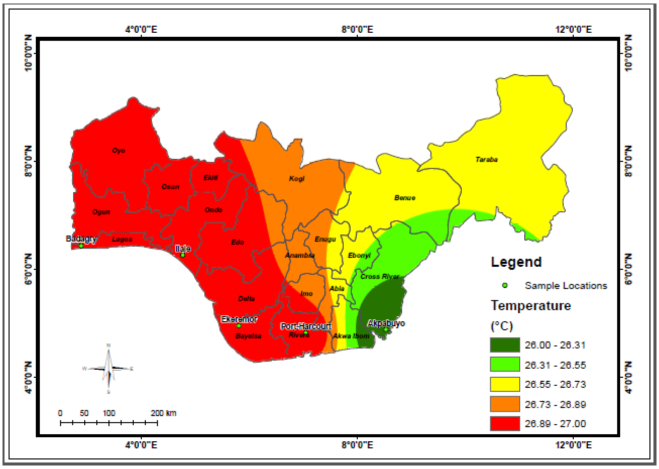

Fig. 10. Spatial distribution of temperature. (Source: ArcMap 10.8)

Furthermore, Table 4 shows the summary of some radio parameters with temperature in the study locations which also revealed that the highest temperature value occurred in Badagry. These results agree with the work of [8].

Table 4: Summary of the mean modified radio refractivity and its gradient with temperature over the study locations

S/N	Locations	M (*M-units*)	M' (*M-units/km*)	M' 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
4	Port Harcourt	474	115	−5	27

4 Conclusion

The results of the effect of temperature at which radio duct occurs in the selected coastal areas of Nigeria have been presented. It was observed that the maximum value of the modified radio refractivity gradient (M’) occurred in Akpabuyo at about 116 M-units/km, while the minimum value occurred in Badagry at about 109 M-units/km. The variations in M' across the different locations suggest that local factors can influence the refractivity characteristics of the atmosphere. Also, M'-values during the wet season are higher than during the dry season. Ducting events occurred sparsely throughout the evaluation period, with occurrences found in December and March (transition from dry to wet season) at Port Harcourt. The results also show that 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. The seasonal patterns in the M' suggest that radio wave propagation conditions in these locations are strongly influenced by changes in atmospheric conditions, such as humidity, temperature, and atmospheric pressure, throughout the year. These findings have important implications for the planning and optimizing the radio communications systems in the region.

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Disclosure of Interest: The authors declare that no competing interests exist.

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