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Spatial and Temporal Distribution of Modified Radio Refractivity Gradient at 875 hPa and 700 hPa over Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Author SEF designed the study. Author VOO performed the statistical analysis. Authors VOO and JSO wrote the protocol and wrote the first draft of the manuscript. Authors SEF and JSO managed the analyses of the study. Author VOO managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The meteorological effects on radio wave signals propagating through the troposphere are of great concerns in the design and performance of radio communication systems. Often, the effect can lead to anomalous propagation conditions such as ducting, super refraction and sub refraction. In this paper, the spatial-temporal distribution of modified radio refractivity gradient and the effects on radio waves propagating at 875 hPa and 700 hPa pressure levels over sixteen selected locations aloft the four climatic regions of Nigeria are investigated. Five (5) years (2013-2017) meteorological parameters namely: air temperature, relative humidity and atmospheric pressure at ground level and 1 km above ground level were obtained from the European Center for Medium-Range Weather Forecast (ECMWF) at four synopses hours of the day. Modified radio refractivity and its gradient at the two pressure levels were computed using ITU- model. Results on a daily and seasonal basis shows similar trends at both 875 hPa and 700 hPa pressure levels, with higher values of modified radio refractivity gradient recorded at 700 hPa heights at the morning and night hours of the day. Results on seasonal basis shows that during the rainy season, modified radio refractivity gradients

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were high. On location basis, Port Harcourt (coastal region) recorded the highest value of modified radio refractivity gradient of about 115.5 M-units/km in the night time (00:00 hr. LT). The value depicts the occurrence of normal refraction in this location. The overall results will be useful for microwave links budgeting and design in Nigeria.

Keywords: Temporal distribution; modified radio refractivity; radio wave signals; radio communication systems.

1. INTRODUCTION

Anomalous propagation conditions in the atmosphere is as a result of changes in atmospheric refractivity with height. The change in atmospheric refractivity is also called duct conditions. However, duct conditions create the multipath fading for propagating signals, and the properties can be investigated with the average gradient of the atmospheric refractive index with geometric height i.e. height above the Earth's surface [1]. There are two components of atmospheric refractivity, namely: vertical and horizontal components. The vertical component of atmospheric refractivity is more important than its horizontal component, and the variation of this component in the troposphere (lowest 1 km) is rather linear, and above this is exponential with geometric height [2]. The profile of the atmospheric refractivity gradient at a height of 1 km above the ground surface is important when studying trapping, super-refraction, sub-refraction and ducting phenomena [3].

All weather phenomena such as temperature difference, density, cloud formation and air pressure takes place in the lower troposphere. In standard atmospheric conditions, water vapour decrease with increasing height more rapidly than temperature. Atmospheric refraction also decreases with geometric height while modified radio refractivity increases with geometric height [4]. The increase in modified refractivity with geometric height gives better clues in finding the ducting regions in the atmosphere than the refractivity gradient [5].

When the modified radio refractivity gradient is constant with geometric height, then the Earth becomes effectively flat to the signal [5]. Mentes and Kaymaz [4], proposed the range of modified refractivity gradient value that can be used to categorize anomalous propagation occurrence as presented in Table 1. In this study, modified radio refractivity gradient with availability of 5-years (2012-2017) satellite data over some selected locations in Nigeria are investigated. Propagation conditions over Nigeria are statistically analysed to assess their influence on microwave radio propagation. Spatial-Temporal maps of modified radio refractivity gradient are generated on monthly basis. The remaining parts of this paper is structured as this: section two is on the theoretical background, section three is on materials and method, section four is on results and discussion while section five is the conclusion.

Table 1. Modified refractivity gradient and corresponding phenomena for the electromagnetic signal propagation [4]

S/N	Modified refractivity gradient (M-units/km)	Conditions	Remarks
1	< 0	Trapping/Ducting	Trapped propagation within the duct boundaries
2	$0 - 79$	Super refraction	Refract downwards towards the Earth's surface, but at a rate less than the Earth's curvature but greater than standard
3	$79 - 157$	Standard/Normal	Refract downwards towards the Earth's surface with a curvature less than the Earth's radius.
4	> 157	Sub refraction	Bend upwards, away from the Earth

Table 2. Characteristics of the locations

S/N	Climatic zone	Location	Lat. (°N)	Long. (°E)	Elevation (m)	Ave. Annual Temp (ºC)	Ave. Annual Rel. Humidity (%)
1	Coastal	Port	4.80	6.98	20.00	26.40	77.67
		Harcourt	4.98	8.33	32.00	26.10	79.42
		Calabar	5.55	5.78	21.00	26.70	77.00
		Warri	6.58	3.33	39.00	26.80	71.33
		Ikeja					
2	Guinea savanna	Benin	6.30	5.60	88.00	26.10	79.00
		Enugu	6.46	7.55	180.00	26.30	66.00
		Ibadan	7.39	3.95	230.00	26.50	81.00
		Akure	7.15	5.12	346.00	28.10	74.00
3	Midland	Jos	9.92	8.90	1217.00	25.00	49.25
		Abuja	9.07	7.39	840.00	30.00	51.75
		Bida	9.08	6.01	118.00	29.00	51.33
		Lafia	8.50	8.50	179.00	27.50	52.50
4	Sub-Sahelian	Maiduguri	11.83	13.15	320.00	25.80	31.00
		Gusau	12.15	6.65	451.00	26.30	34.25
		Sokoto	13.00	5.30	296.00	28.40	27.92
		Kano	11.98	8.48	481.00	26.40	31.00

2. THEORETICAL BACKGROUND

The deviation of refractive index (*n*), from unity is very small in absolute terms, a typical value being 1.0003 at the earth's surface. Because of the closeness of *n* to unity, it is usual to work with the refractivity, *N*, defined by:

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

where N is dimensionless, but for convenience, it is measured in *N*-units. *N* depends on the pressure *P* (hPa), the absolute temperature *T* (K) and the partial pressure of water vapour (e) (mbar). *N* is related with these parameters as:

$$N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (2)$$

Equation (2) is divided into two parts,

$$N = N_{DRY} + N_{WET} \quad (3)$$

where

$$N_{DRY} = 77.6\frac{P}{T} \quad (4)$$

and

$$N_{WET} = 3.73X10^5 \frac{e}{T^2} \quad (5)$$

where *P* is the atmospheric pressure (hPa), *e* is the water vapour pressure (hPa) and *T* is the absolute temperature in Kelvin. *e* can be expressed as:

$$e = \frac{He_s}{100} \quad (6)$$

where

$$e_s = a \exp\left(\frac{bt}{t+c}\right) \quad (7)$$

where *H* is the relative humidity (%), *t* is the average surface ambient temperature (°C) for the period of a month. e_s is saturation water vapour pressure (hPa) at the temperature *t* (°C). The coefficients a, b, c are 6.1121 hPa, 17.502 hPa and 240.97 (℃) as provided by ITU-R, P.453-13 (2017).

The expression when the average *N* decreases exponentially in the troposphere is:

$$N = N_s\, exp(\frac{-z}{H}) \quad (8)$$

where, Ns is the surface value of refractivity, z is the height above the surface and H is the scale height. Instead of *N*, in practice *M* is used, which includes the effect of the earth curvature. Also, in radio propagation assessment, it is convenient to use *M* [6].

Modified radio refractivity *M* is related to radio refractivity by

$$M = N + \frac{z}{R_e \times 10^{-6}} \quad (9)$$

$$M = N + 157 \times z \quad (10)$$

where

N is the radio refractivity,
M is the modified radio refractivity,
R_e is the Earth's radius approximately 6371 km and,
z is geometric height i.e. the height in kilometers above sea level. (Recommendation ITU-R, 2017 P.453-7)

Modified radio refractivity gradient can therefore be computed using:

$$\frac{dM}{dz} = \frac{M_h - M_s}{z_h - z_s} \quad (11)$$

where M_h is the modified radio refractivity at 700 hPa and 875 hPa which is equivalent to 2.7 km and 1 km, M_s is the modified radio refractivity at the surface level, z_h is geometric height above sea level in km and z_s is height at the surface level. The bulk of the meteorological parameters that affect radio refractivity are in the first 1 km layer of the troposphere. Radio refractivity also varies exponentially at a layer above 1 km in the troposphere, hence the choice of these heights for this study.

3. MATERIALS AND METHODS

Meteorological parameters namely: air temperature, relative humidity at ground level and 1 km above sea level for five years (2013-2017) were obtained from the European Center for Medium-Range Weather Forecast (ECMWF) at four synopses hours (00:00, 06:00, 12:00, 18:00 hour Local Time) of the day and at a grid of $0.75° \, x \, 0.75°$. The data assimilation system used to produce Era-interim is based on a 2006 release of the IFS (Cy31r2). The system includes a 4-dimensional variational analysis (4D-var) with a 12-hour analysis window. The spatial resolution of the data set is approximately 80 km (T255 spectral) on 60 vertical levels from the surface up to 0.1 hPa. Era-interim data are always updated once in a month to allow for quality assurance. With the use of Microsoft excel package, the yearly (2013-2017) data was averaged into a single year i.e. the averages of all the data sets for the five years where taken based on the four different synoptic hours of the day and at both pressure levels.

Diurnal, seasonal as well as occurrence probability plots of modified radio refractivity gradient were presented using the excel package. The spatial-temporal maps were also presented using the kriging tool on the Arc-GIS software.

4. RESULTS AND DISCUSSION

4.1 Diurnal Variation of Modified Radio Refractivity Gradient

Fig. 1 (a-d) shows the diurnal variations of modified radio refractivity gradient in the month of February which represents the peak of the dry season months across all the locations at the two pressure levels. In Calabar (Fig. 1(a) for example) which represents the coastal region, the highest value of modified refractivity gradient at both pressure levels was recorded during 18:00 hr. LT with a value of 95.66 M-units/km and 113.82 M-units/km respectively. These results depict the occurrence of normal refraction at these pressure levels. The maximum value of modified radio refractivity gradient in Akure was recorded at the 06:00 hr. LT of the day with a value of about 90.34 M-units/km and 113.80 M-units/km at 875 hPa and 700 hPa levels respectively. These results agree with the work of Ojo *et. al.,* [7] that radio waves will be propagated normally at this time window in Guinea Savanna region like Akure. In Lafia (Midland region) and Akure (Guinea Savanna region), the lowest values of modified radio refractivity gradient were recorded at 12:00 hr. LT of the day. This is due to the increase in air temperature in these locations and at this time window. Fig. 1 (b-d) also shows that super refractive conditions prevailed in Akure, Lafia and Sokoto at 06:00 hr. LT and 12:00 hr. LT. Fig. 2 (a-d) shows the diurnal variations of modified radio refractivity gradient in the month of July which represents the peak of the wet season month across all the locations at the two pressure levels. Modified radio refractivity gradient values were observed to be generally high at both pressure levels, across all the climatic regions and at all times of the day. The highest value of modified radio refractivity gradient was recorded in Akure (Guinea Savanna region) at the 18:00 hr. LT with a value of 106.46 M-units/km at 875 hPa pressure level. In Akure (Guinea Savanna region) and Sokoto (Sub - Sahelian region), similar trend was observed at 875 hPa pressure level. The lowest value of modified radio refractivity gradient being recorded at the morning time (06:00 hr. LT) as

87.8 M-units/km and 93.3 M-units/km respectively. This is due to reduction in the amount of water vapour content in these locations and at this time window. Similar trend was observed in the variation of modified radio refractivity gradient with time in Calabar (Coastal region) and Lafia (Midland region). It was also observed that at 875 hPa pressure level, the lowest value of modified radio refractivity gradient at these locations was recorded at 12:00 hr. LT as 97.21 M-units/km and 92.77 M-units/km. Higher values of modified radio refractivity gradients recorded on a diurnal basis in the month of July at both pressure levels depicts the occurrence of normal refraction.

4.2 Seasonal Variation of Modified Radio Refractivity Gradient

Modified radio refractivity varies with seasons of the year [8]. This section therefore presents the seasonal variations of modified radio refractivity gradient at the two pressure levels. One location in each climatic zone is chosen which include, Calabar (Coastal), Ibadan (Guinea Savanna), Abuja (Midland) and Maiduguri (Sub-Sahel). Fig. 3. (a-d) presents the seasonal variation of modified radio refractivity gradient at 875 hPa level across the four climatic regions of Nigeria. Similar trends were observed with the highest value of modified radio refractivity gradient recorded between the months of July and September which happens to be the peak of the rainy periods for these regions. In Fig. 3 (a and b) for example, there is a steady increase from January to March and a sharp drop in April and May. This may be due to the fact that the month of April and May are the transition months and experiences drop in water vapour content in the atmosphere. In Ibadan (Fig. 3 (b)) and Abuja (Fig. 3 (c)), a steady increase in the value of modified radio refractivity gradient occurred from April to October and a sharp drop from November to December which represents the dry season months for these locations. At 875 hPa level, the highest value of modified radio

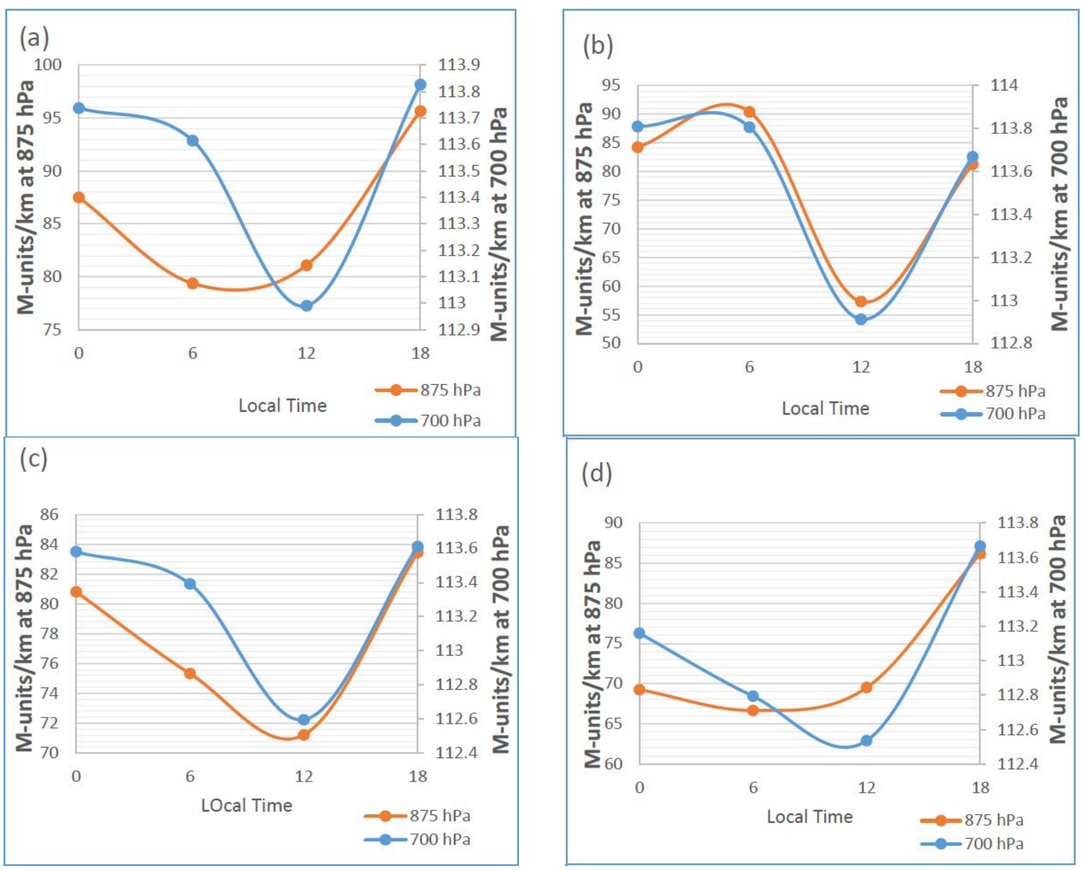


Fig. 1. Diurnal variation of modified radio refractivity gradient in February (Dry season month) at 700 hPa and 875 hPa for (a) Calabar (b) Akure (c) Lafia (d) Sokoto

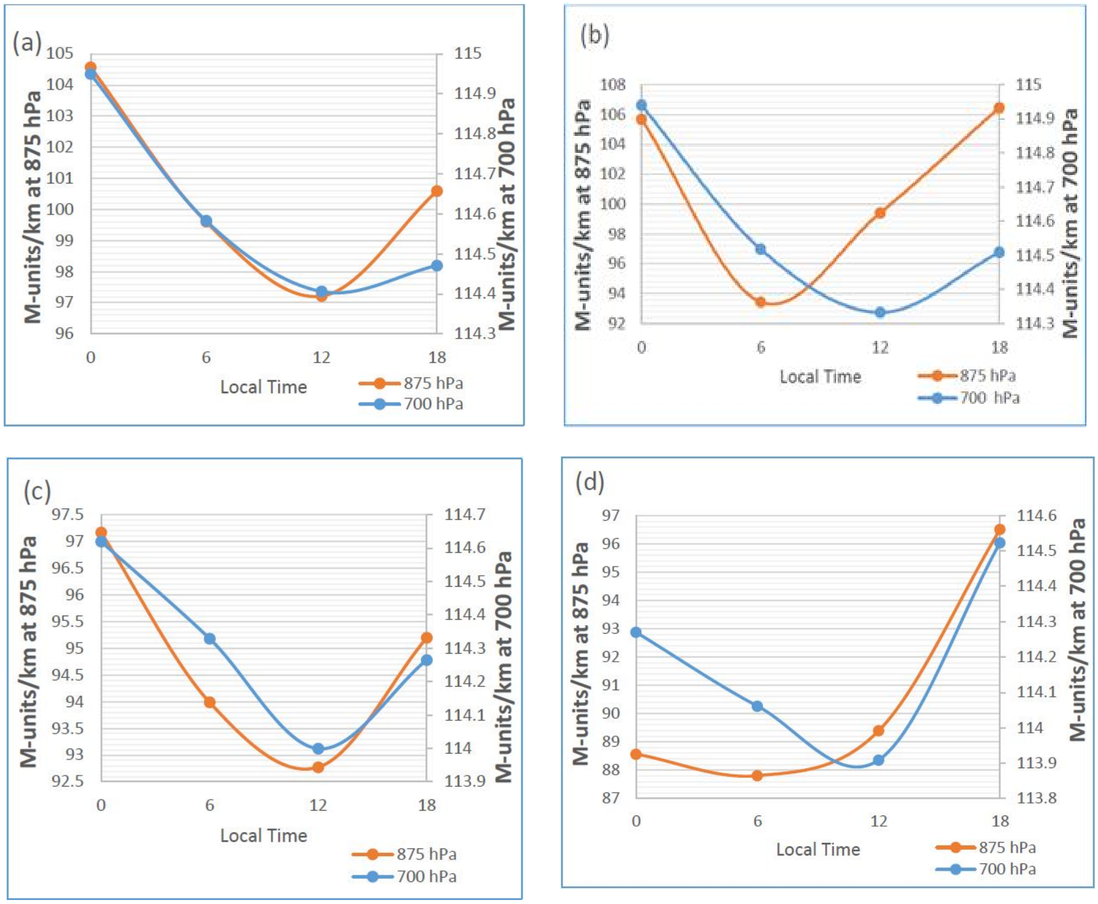


Fig. 2. Diurnal variation of modified radio refractivity gradient in July (wet season month) at 700 hPa and 875 hPa for (a) Calabar (b) Akure (c) Lafia (d) Sokoto

refractivity was recorded in Calabar (Coastal region) as 104.05 M-units/km at the 18:00 hr. LT in the month of July. These results show the occurrence of normal refraction in this region. The least value of modified radio refractivity was recorded in Abuja (Midland region) as 39 M-units/km at the 00:00 hr. LT in the month of January. These results show the occurrence of super refraction in this region. Fig. 4 (a-d) shows the seasonal variation of modified radio refractivity gradient at 700 hPa level across the four climatic regions of Nigeria. Similar trends were observed all through with the peak of modified radio refractivity gradient occurring in the months of July and August as 114.71 M-units/km and 114. 83 M-units/km respectively. The least values were recorded in the months of February and March as 112.9 M-units/km and 112.8 M-units/km respectively. The overall results of the seasonal variation show different anomalies within the climatic regions.

4.3 Probability Occurrence

Figs. 5 – 8 (a-d) present the summary of the percentage of occurrence of super refraction and normal refraction events at the four synopsis hour of the day at 875 hPa. Percentage of occurrence of propagation conditions at 700 hPa was not shown because from the diurnal variations, it can be seen that only normal refraction occurred throughout. As shown in Fig. 5 (a-d), results for Bida (Midland region) station show that the rainy months of June – September are dominated by normal refraction with 100% percentage of occurrence. It can also be shown that there was 100% percentage of occurrence of super refraction in the dry season months of December, January and February respectively. A very low percentage of super refraction was observed in October at 00:00 hr. LT. Fig. 6 (a-d) shows that in Warri, at 00:00 hr. LT and 18:00 hrs. LT, there were few occurrences of super refraction up to 10% in January and approximately 8% in February and the least of about 5% in December which are the Dry months. It can be observed in Akure (Fig. 7 (a-d)) for example, that there was high occurrence of super refraction mostly from the months of December to February. January recorded 100% occurrence of super refraction at 12:00 hrs. LT as the peak of the dry season months. This implies that at these periods of the year, stations around Akure and in turn in the Guinea Savanna region will be opened to severe interference from distant stations due to the effect of high occurrence of super refraction. This interference may result in frequent signal outage from the stations. In can also be shown that in Maiduguri (Fig. 8 (d)), at 18:00 hrs. LT, super refraction only occurred from December (onset of the Harmattan period) to February (peak of the dry season months).

4.4 Spatial – Temporal Distribution of Modified Radio Refractivity Gradient

Fig. 9 (a-b) shows the spatial distribution of modified radio refractivity gradient during the 12:00 hr. LT window at 875 hPa and 700 hPa respectively. It can be observed that the Coastal region recorded the highest values of modified radio refractivity gradient while the Midland region recorded the least values at 875 hPa and least values of modified radio refractivity gradient was recorded in the Sub-Sahel region of about 88 M-units/km at 700 hPa. The seasonal and diurnal variations of the wet term in refractivity Eq. (6) have been observed to correlate with the variation of VHF (Very High Frequency) and UHF (Ultra High Frequency) field strength as reported in the work of Owolabi and Williams [9].

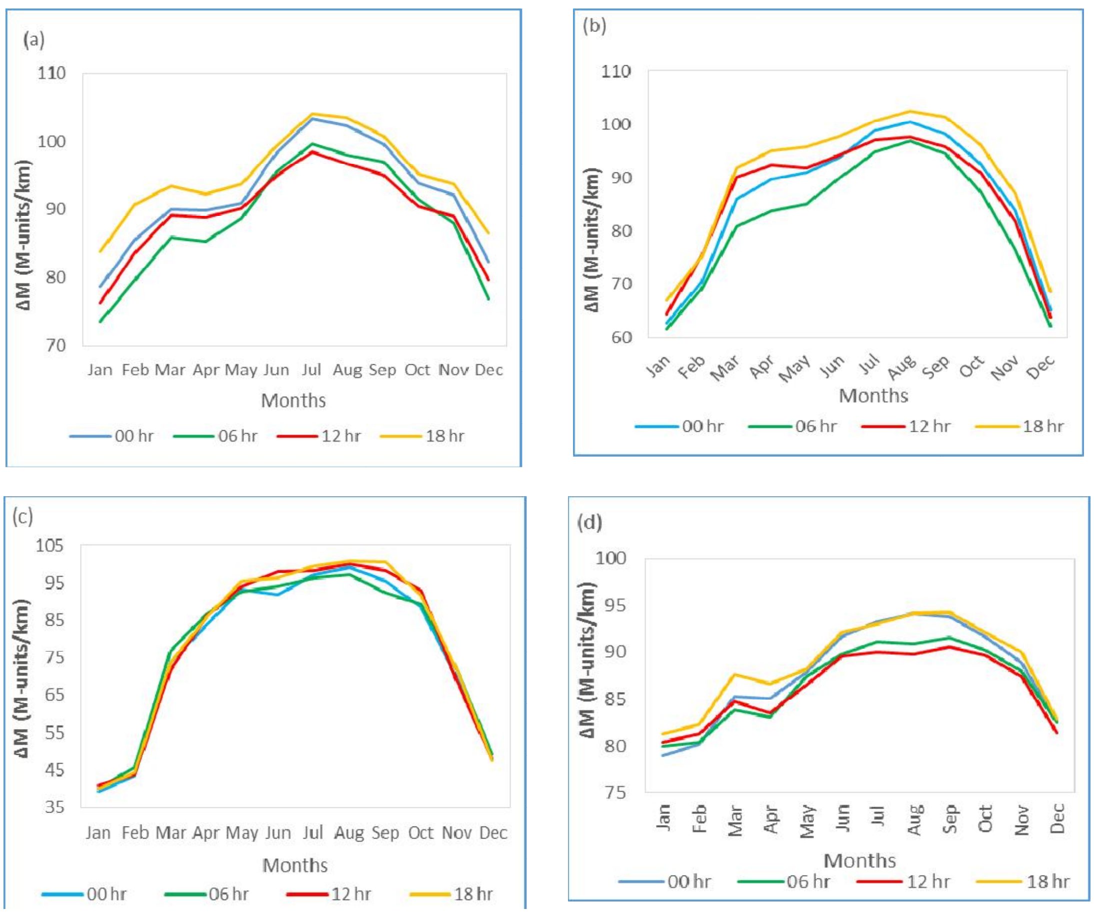


Fig. 3. Seasonal variation of modified radio refractivity gradient (M-units/km) at 875 hPa for (a) Calabar (b) Ibadan (c) Abuja (d) Maiduguri

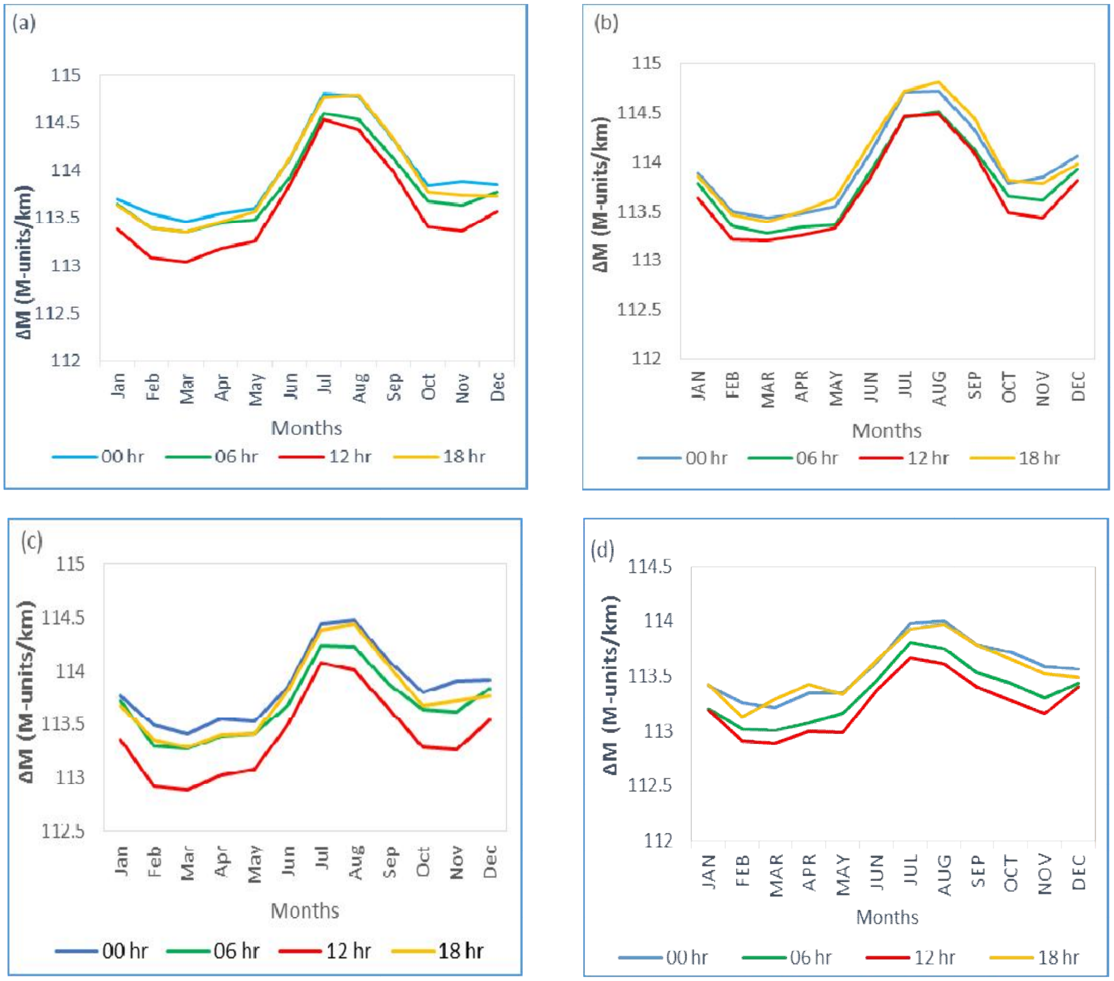
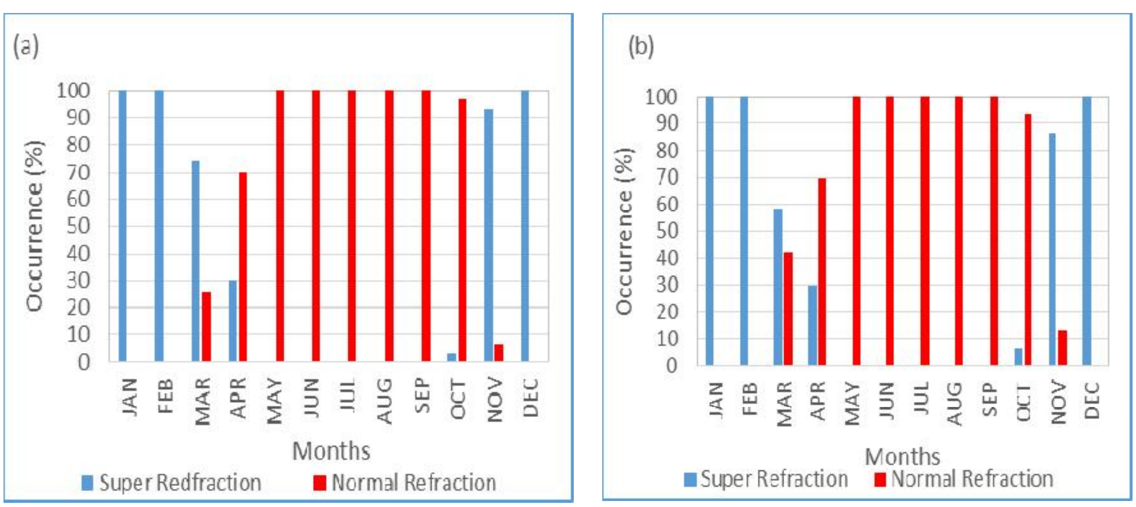


Fig. 4. Seasonal variation of modified radio refractivity gradient (M-units/km) at 700 hPa for (a) Calabar (b) Ibadan (c) Abuja (d) Maiduguri



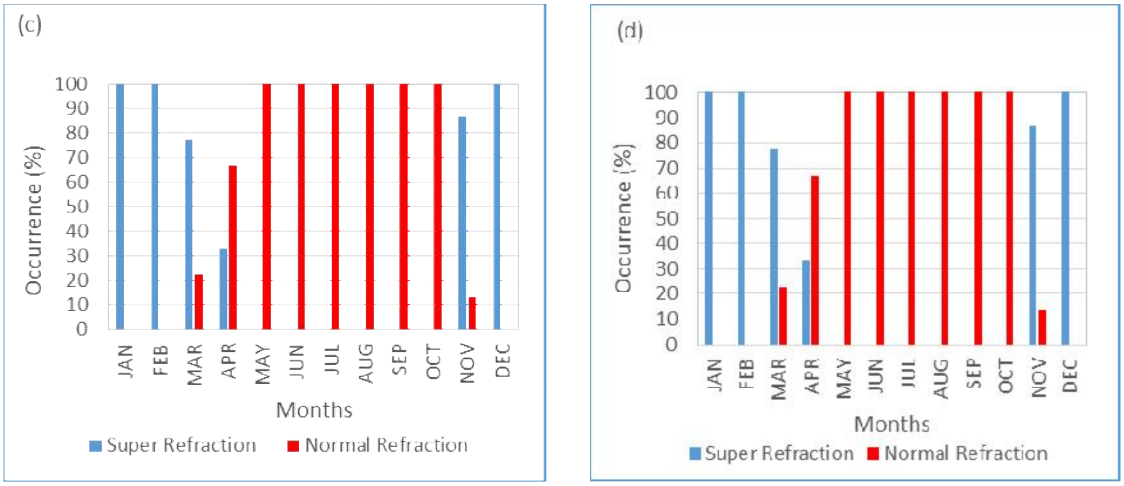


Fig. 5. Percentage occurrence probability of propagation condition for Midland region (Bida) at 875 hPa level (a) 00:00 hr. LT (b) 06:00 hr. LT (c) 12:00 hr. LT (d) 18:00 hr. LT

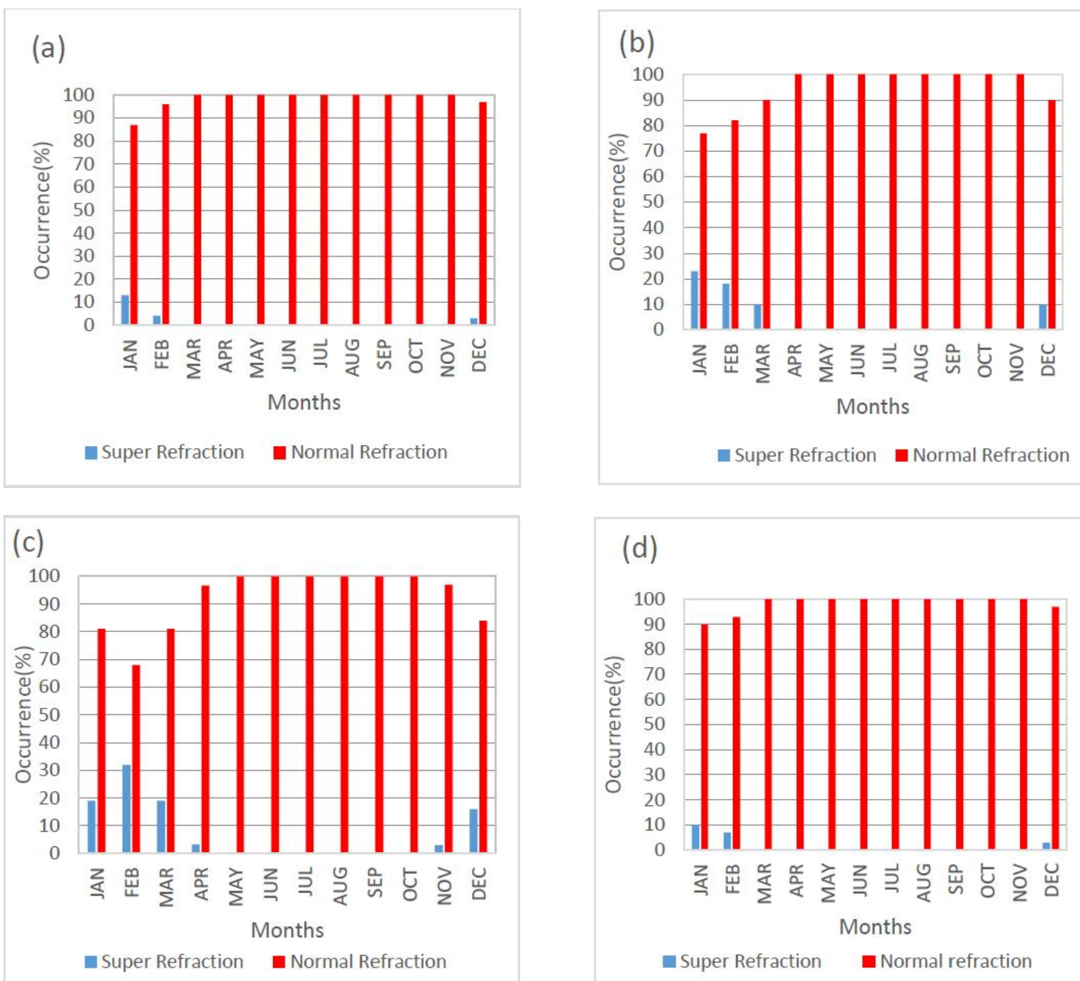


Fig. 6. Percentage occurrence probability of propagation condition for Coastal region (Warri) at875 hPa level (a) 00:00 hr. LT (b) 06:00 hrs. LT (c) 12:00 hrs. LT (d) 18:00 hrs. LT

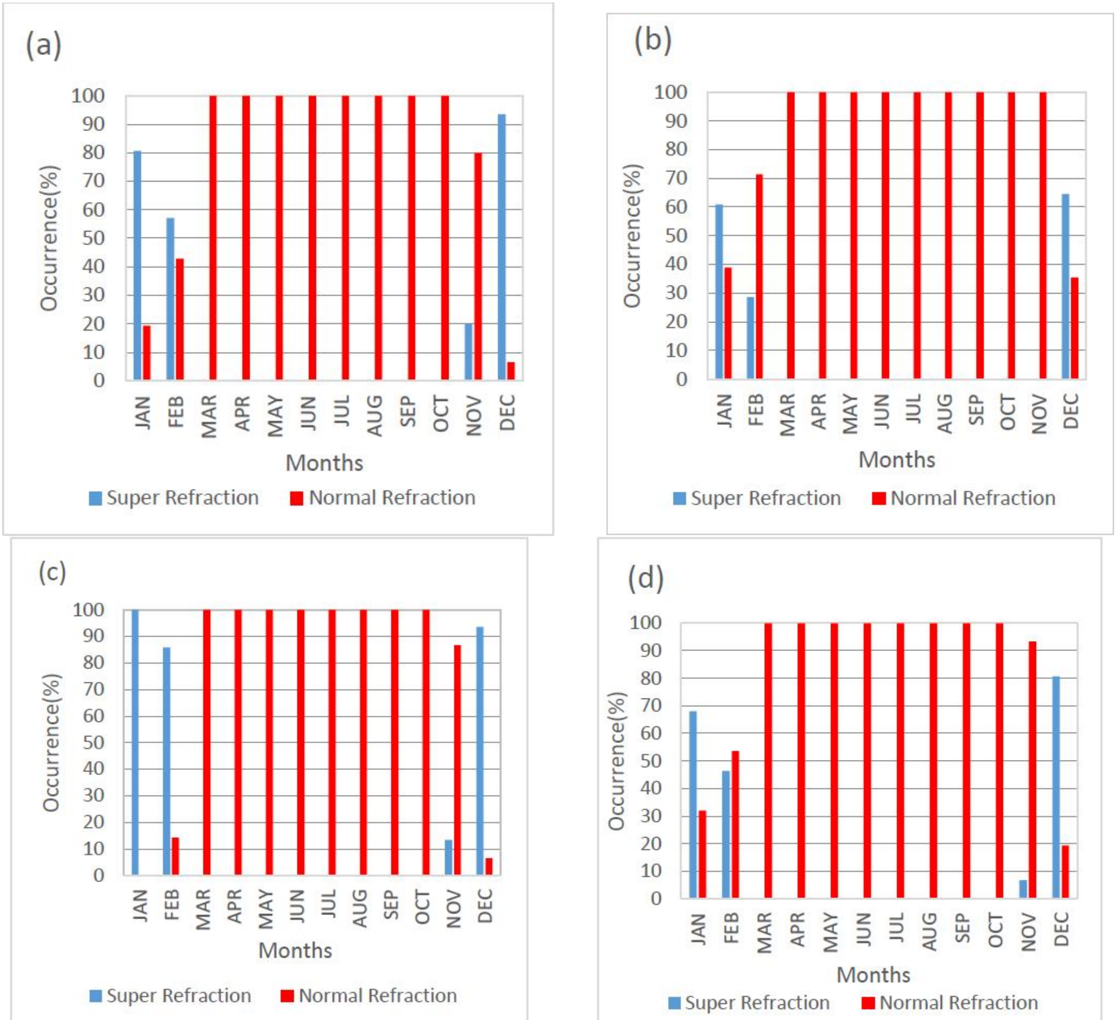
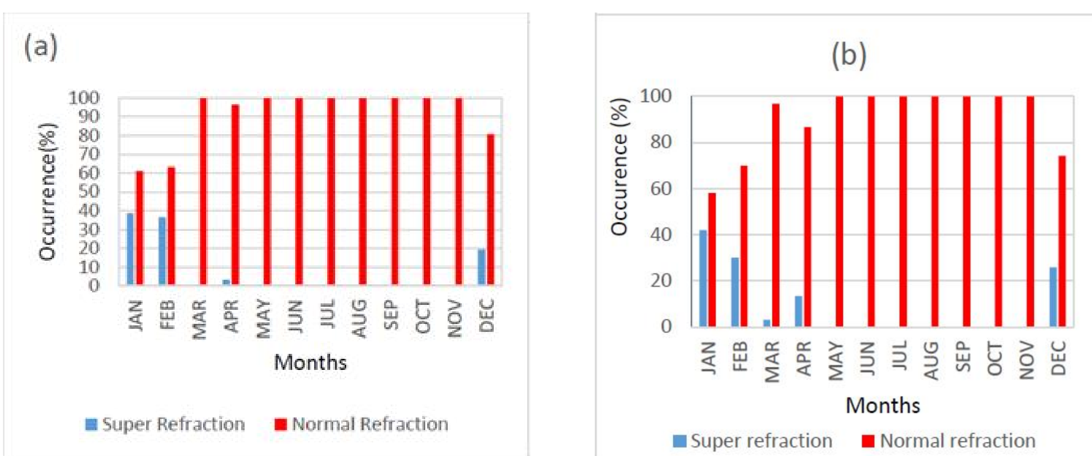
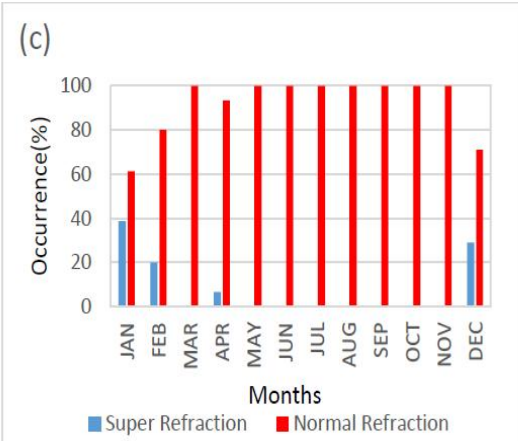


Fig. 7. Percentage occurrence probability of propagation condition for Guinea Savanna region (Akure) at 875 hPa level (a) 00:00 hr. LT (b) 06:00 hrs. LT (c) 12:00 hrs. LT (d) 18:00 hrs. LT





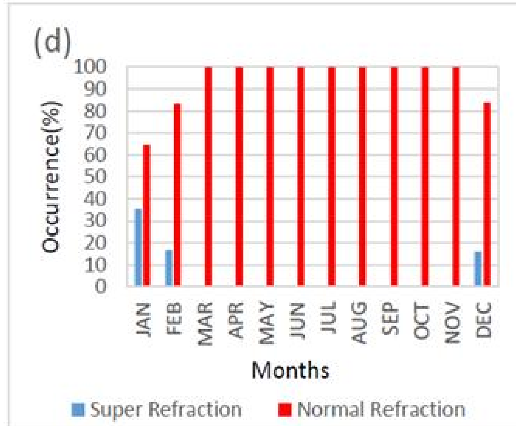
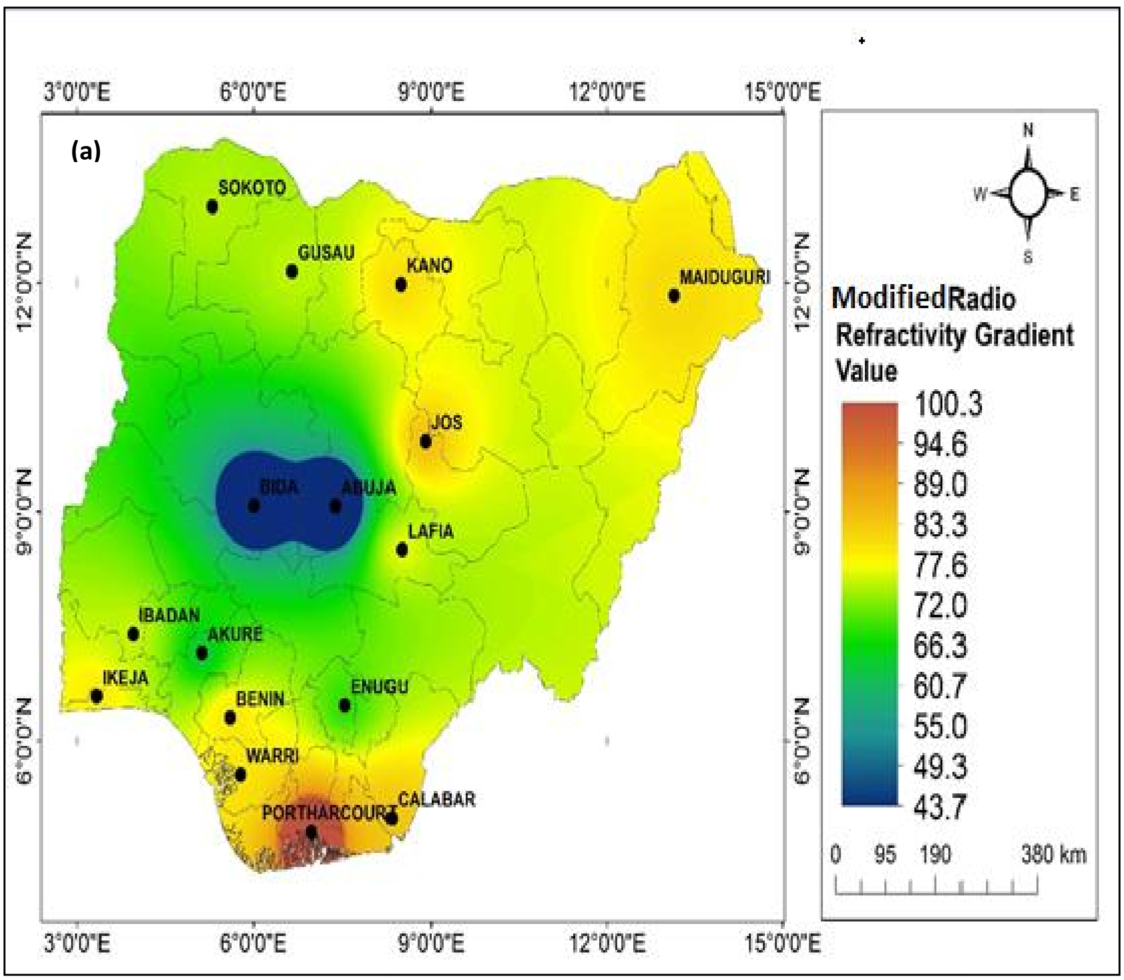


Fig. 8. Probability occurrence probability of propagation condition for Sub-Sahel region (Maiduguri) for 875 hPa level (a) 00:00 hr. LT (b) 06:00 hrs. LT (c) 12:00 hrs.LT (d) 18:00 hrs. LT



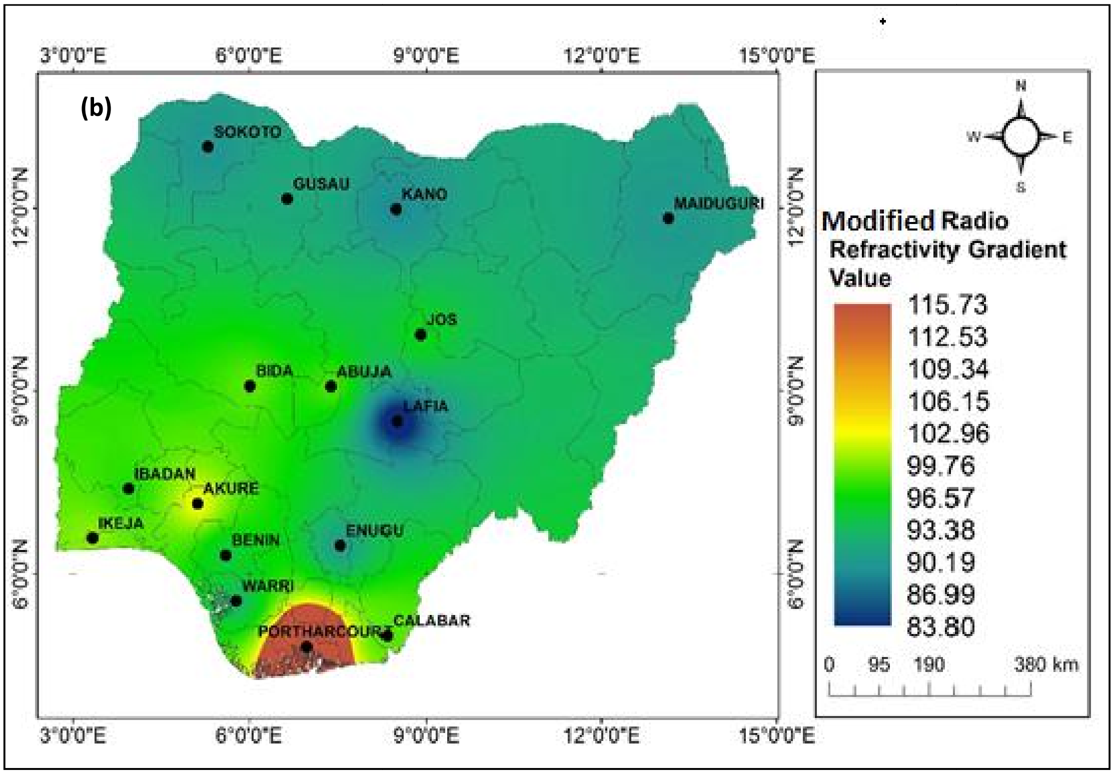


Fig. 9. Spatial- temporal distribution of modified radio refractivity gradient at 12:00 hr. LT (a) 875 hPa (b) 700 hPa

5. CONCLUSION

Recent results of the spatial and temporal distribution of modified radio refractivity gradient at 875 hPa and 700 hPa over Nigeria has been presented. It was observed that the maximum values of modified radio refractivity gradient averaged over the month occurred at 18:00 hr and the minimum values occurred at 12:00 hr. The results generally showed that the modified radio refractivity gradient values for the wet months were higher than the values in the dry season months. Also, modified radio refractivity gradient values vary seasonally with height; as the maximum value of 114.88 M-units/km was in August, while the minimum value of 39 M-units/km was in January. It was also shown spatially, that the highest value of modified radio refractivity gradient was recorded in the Coastal region. This implies that, radio waves signal will be propagated normally in this region at 700 hPa pressure level. The overall results will help mobile communication circuit designers to plan and design communication systems that will make radio propagation at these pressure levels possible for better and unhindered communication link.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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