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ORIGINAL PAPER

Tropospheric radio refractivity trends over vegetation regions in Nigeria

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Abstract
Refractivity is an important parameter in understanding radio wave propagation in the troposphere. We investigated both the monthly variations of refractivity and its trends over vegetation regions in Nigeria. Application of Matlab program was used to compute the values of radio refractivity from meteorological variables for a period 1979–2013, using ITU-R P 453-12 (The radio refractivity index; its formula and refractivity data. Recommendations and reports Geneva Switzerland, 2016) model. Results show that the pattern of radio refractivity variation at various locations in Nigeria is not the same due to the different vegetation regions. The states within the Freshwater and Rainforest regions were found to have higher refractivity values than those in the Guinea savannah, Sudan savannah and Sahel savannah regions in Nigeria. The Guinea savannah region of Nigeria (called the middle belt) has the same trend with the other parts of savannah regions in Nigeria. The only difference found is in the refractivity values. The mean refractivity values revealed that the Guinea and Sahel savannah regions have higher refractivity values than Sudan savannah region while, the Sahel savannah region has lower refractivity values than Guinea savannah region. The trends of refractivity show that refractivity increases by 0.1 N units per year in the Freshwater and Rainforest regions and decreases by 0.1 N units per year in the savannah regions of Nigeria. The average monthly value of refractivity increases from a value of approximately 356 N units in Sudan savannah region to maximum value of approximately 382 N units in Freshwater region. This indicates that the radio refractivity value increases from the savannah region to the Freshwater region of Nigeria. It was also observed that the Guinea savannah region radio refractivity values were lower than those of the Freshwater and Rainforest regions, but greater than those of the Sudan and Sahel regions. This observation is coherent with the knowledge that the Rainforests (south of the Nigeria) are more humid than the dry climates (north of the Nigeria), and so the Rainforests have greater refractivity values than the Sudan and Sahel regions. The Guinea savannah which is geographically located between these two sets of regions has moderate refractivity values.

1 Introduction

A wave is an oscillation or periodic movement that can transport energy from one point in space to another. Electromagnetic (EM) waves consist of an electric field oscillating in step with a perpendicular magnetic field, both of which are perpendicular to the direction of travel. EM waves can travel through a vacuum at a constant speed of approximately 3.0×10^8 m/s, which is the same as the speed of light. Therefore, electromagnetic waves are waves that do not require a medium for their propagation. The atmospheric dynamics affect the propagation of electromagnetic waves. Variability in the atmospheric compositions changes temperature, relative humidity and air pressure, these changes influences propagation of electromagnetic waves due to its ability to reflect, refract, scatter and absorb by different atmospheric components within the troposphere. Troposphere is the lowest layer of the Earth's atmosphere at a depth of approximately 17 km at the middle latitudes, 20 km deeper in the tropics and about 7 km shallower near the Polar regions (Russell 2010). The troposphere is the region of the atmosphere that all the familiar earth weather takes place. Khurram et al. (2018) mentioned that the power of signal, the frequency of operation and the tropospheric condition through which radio waves propagates contributed to the strength of atmospheric effects on radio waves propagation.

Adediji and Ajewole (2011) also show that radio refractive index is an essential factor of a propagation model to

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calculate radio propagation in the troposphere. It has been revealed that sometimes radio or micro waves systems could become inaccessible due to the seasonal variation of refractive index (Serdega and Ivanovs 2007; Safdar et al. 2012). Hence, the accurate information on radio refractivity is very necessary in the planning and design of terrestrial radio links for communication networks, radar and propagation applications, etc. (Caglar et al. 2006; Naveen et al. 2011).

The study on seasonal and diurnal tends of surface refractivity in a tropical environment of Nigeria by Yusuf et al (2019) concluded that month-to-month variability for the tropospheric surface refractivity *N*, recorded the highest value in the rainy season and lowest value in the dry season in the areas investigated. Agbo et al. (2021a) on analyzing the effects of meteorological parameters on radio refractivity also concluded that the radio refractivity is directly affected by the water vapor content of the atmosphere as the months with the highest relative humidity are observed to have the highest refractivity. In a related study, Nzeagwu et al. (2021) conducted a comparative assessment of radio occultation-based refractivity measurements from the COSMIC mission (at 1 km altitude) and in situ atmospheric measurements (on ground) in equatorial Africa. They found that the in situ surface refractivity values were higher than the COSMIC refractivity values (at 1 km) irrespective of the season and time of the day. This supports the fact that refractivity decreases with increasing altitude. Ukhurebor and Nwankwo (2020) showed in their study of estimation of the refractivity gradient from measured essential climate variables in Iyamho-Auchi, Edo State, South-South Region of Nigeria, that the months with low relative humidity values were having higher refractivity gradient values compared to those with higher relative humidity.

Work has been done on radio waves propagations and tropospheric radio links design. Amongst the researchers who have done some investigations on the area of lower atmospheric (troposphere) refractivity and contributed to its development include (Adeyemi and Emmanuel 2011; Ayantunji et al. 2011a, b, c; Emetere et al. 2015; Adediji et al. 2015; Bawa et al. 2015; Adedayo 2016; Tanko et al. 2019; Fashade et al. 2019; Agbo et al. 2020, 2021b). However, none of the above-mentioned work shows how radio refractivity trends vary within vegetation regions in Nigeria. This serves as a motivation for the present study. Hence, the objective of the study is to determine the tropospheric radio refractivity trends over thirteen selected stations/states within five vegetation regions in Nigeria for the period (1979–2013). The selected stations/states include Bayelsa and Rivers which are located within the Freshwater Region; Imo, Osun and Ondo located within the Rainforest Region; Kwara, Abuja and Niger located within the Guinea savannah region; Adamawa, Bauchi and Sokoto located within the Sudan savannah region; Yobe and Borno located within the Sahel savannah region. Table 1 presents the coordinates of the selected stations/states and their data points over Nigeria, while Fig. 1 shows the grid maps of selected stations/states and their locations in Nigeria.

Nigeria is classified into various vegetation's types. Freshwater swamp region is one of the main types of vegetation in the forest zone of Nigeria. It is a vegetation with different species and among the productive ecosystems of the world. It is found in Niger Delta region of the country. The Rainforest regions is an important vegetation in most areas within Nigeria. It is found mostly along the right bank of lower reaches of the River Niger and in the valley of River Cross. The Guinea savannah region is the largest vegetation region in Nigeria. It covers almost half of Nigeria territory. This constitutes the most extensive vegetation zone located in the middle belt of the country, and typically consists of trees and grasses. The Sudan savannah region located in northern Nigeria forms a broad vegetation belt covering almost one quarter of the country's landmass. Landscape

Table 1 Coordinates of the selected station/state and their data points over Nigeria

Point	State	Station	Vegetation type	Latitude (°N)	Longitude (°E)
1	Bayelsa	Apoi Creek	Freshwater	4.59	5.84
2	Rivers	Offshore	Freshwater	4.25	7.25
3	Imo	Obiohoro Osu	Rainforest	5.75	7.25
4	Osun	Mowo	Rainforest	7.25	4.25
5	Ondo	Idosale	Rainforest	7.25	5.75
6	Kwara	Pategi	Guinea Savannah	8.75	5.75
7	Abuja	Kabi	Guinea Savannah	8.75	7.25
8	Niger	Luma	Guinea Savannah	10.25	4.25
9	Adamawa	Mubi	Sudan Savannah	10.25	13.25
10	Bauchi	Dindima	Sudan Savannah	10.25	10.25
11	Sokoto	Gudu	Sudan Savannah	13.25	4.25
12	Yobe	Damaturu	Sahel Savannah	11.75	11.75
13	Borno	Dalori	Sahel Savannah	11.75	13.25

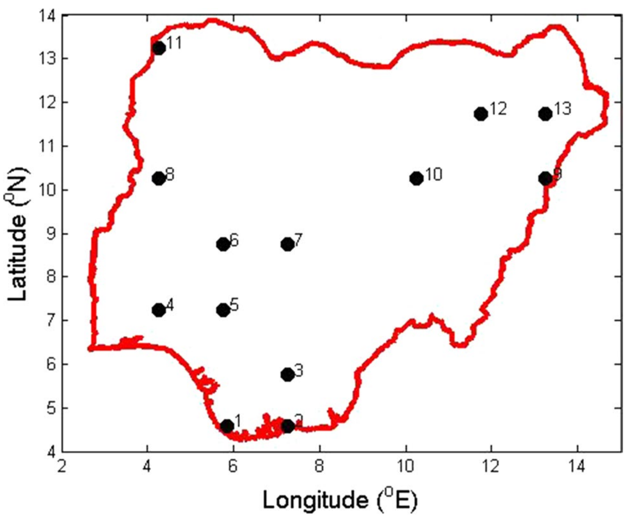

Fig. 1 Grid map of selected stations/state in Nigeria

is typically characterized by a dense shrub and grass layer, with a minor tree component, thus with less abundance of tree and grass species relative to this region. The Sahel savannah region ecological zone is located in the farthest northern regions of the country and is the driest of all the savannah regions. It is characterized by dense tangles of deciduous climbers and scandent shrubs that alternate with open patches of tall grasses, larger trees are more or less isolated. However, landscape is more open with smaller trees. Overall, these different vegetation futures present different meteorological conditions specifically variability in air temperature, relative humidity and air pressure, which are determinants of tropospheric radio wave propagation.

2 Data and methods

The satellite datasets used for this study covers the period 1979–2013 for thirteen (13) grid point stations that span through 13 states in Nigeria (Fig. 1). The datasets generated and analyzed during the current study are available in the web archive of the ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (ECMWF). website: https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/.

2.1 Radio refractivity measurement

The tropospheric radio refractivity for five vegetation regions in Nigeria was measured by indirect method. The five vegetation regions investigated include Freshwater region, Rainforest region, Guinea savannah region, Sudan savannah region and Sahel savannah region. The atmospheric parameters such as temperature, relative humidity and pressure values were obtained from the measurements generated in the ERA-Interim data. The data which were in NetCDF format were extracted, converted to binary format, sorted and merged to file using Matlab software program. The values of air pressure (hPa), temperature (°C), and relative humidity (%) were extracted for the period (January 1979–December 2013).

The daily data collected over all the states within the vegetation regions were used to determine the tropospheric radio refractivity values using the ITU-R P 453-12 (2016) model. The modified formula is given in Eqs. (1) to (3).

$$N = 77.6\frac{P_{\mathrm{air}}}{\mathrm{T}} + 373256\frac{P_{\mathrm{w}}}{T^2}, (\mathrm{N\ units}) \tag{1}$$

where P_{air} is the air pressure or for simplicity pressure in Hectopascal (hPa), P_{w} is the water vapor pressure in Hectopascal (hPa) and T is the absolute temperature in Kelvin (K).

The relative humidity, RH (%) and water vapor pressure, P_{w} (hPa) is related by Eq. (2),

$$P_{\mathrm{w}} = \frac{\mathrm{RH}.P_{\mathrm{s}}}{100}, \tag{2}$$

where p_{s} is the saturation vapor pressure.

The pressure in the air saturation that increases with increasing temperature is referred to as the saturation vapor pressure, p_{s}. The computation of saturation vapor pressure, p_{s} is done using the ITU-R P 453-12 (2016) formula is given by Eq. (3).

$$P_{\mathrm{s}} = 6.1121\exp\left\{\frac{17.502 \times t}{t + 240.97}\right\}, \tag{3}$$

where P_{s} is the saturated vapor pressure and t is the value of the temperature in degree Celsius (°C).

The conversion factor from degree Celsius (°C) temperature to Kelvin (K) is given by Eq. (4)

$$T(\mathrm{K}) = T_{\mathrm{C}} + 273.15, \tag{4}$$

where T (K) is temperature in Kelvin (K) and T_{C} is temperature in degree Celsius (°C).

The refractive index, n and refractivity, N are related by the Eq. (5), ITU-R (2012).

$$n = \left(N \times 10^{-6}\right) + 1. \tag{5}$$

2.2 The plotting procedure

Daily scale radio refractivity values for the study periods were obtained and monthly means are computed, also from the obtained results we computed the seasonal averages over the five vegetation regions under investigation. The monthly averages were averaged in monthly bins, to obtain the yearly values of tropospheric radio refractivity over all the years investigated. Furthermore, the yearly averages were carried out based on each vegetation regions in Nigeria, and these were used to investigate the tropospheric radio refractivity trends over the five vegetation regions under consideration. The analyses were all achieved using Matlab software.

3 Results and discussion

3.1 Average monthly refractivity values over freshwater region

Figure 2 provides the computed averaged monthly results of refractivity for 35-year period under study (January 1979–December 2013) in Freshwater region. The refractivity values in this region show a pattern similar to sinusoidal wave pattern. The peak and lowest values of refractivity were observed in the month of April and December, respectively for this region. The reason for the highest value of refractivity experienced in April occurred because of rainy season within this period that caused the atmosphere to be humid, thereby causing high value of humidity and low temperature value. Also, the lowest refractivity value observed in December is due to the fact that this region experienced dry air or harmattan within this period. In other words, this period experienced low humidity value. This result is in agreement with Agbo et al. (2021b) that the average refractivity for the wet months were higher than the average refractivity for the dry months.

The refractivity values in Fig. 2 maintained a steady increment of about 375.10 N units in January till a maximum value of about 381.67 N units in April. It follows a steady fall till July from which it has a slightly uniform value till August before it slightly rises again to October and then falls to another minimum value of about 373.62 N units in December. This shows that there is no much variation between the dry months (November–February) and rainy months (March–October) in this region because during the dry months the evaporation from the Atlantic Ocean around this region makes the area to have high values of refractivity. The noticeable drop in the values of refractivity between July and August in this region may be associated to August break, that is, a short period of scanty rainfall or dryness.

3.2 Average monthly refractivity values over rainforest region

Figure 3 depicts the average monthly values of refractivity for a 35-year period (January 1979–December 2013) over the Rainforest region. The refractivity values in this region show a pattern with high values of refractivity in the months of March–October and low values in the months of November–February. The high values of refractivity between the months of March and October are due to high humid air attributed to rainy season within the period. The humid atmosphere caused a decrease in temperature and high humidity. This episode of high humidity increases the refractivity values during the rainy season in Nigeria. The low refractivity value observed in the months of November–February is attributed to dry season that caused the atmosphere to be dry. This effect causes the humidity values to drop and increases the temperature values. The highest and lowest values of refractivity were observed in the months of October and December, during the rainy and dry seasons,

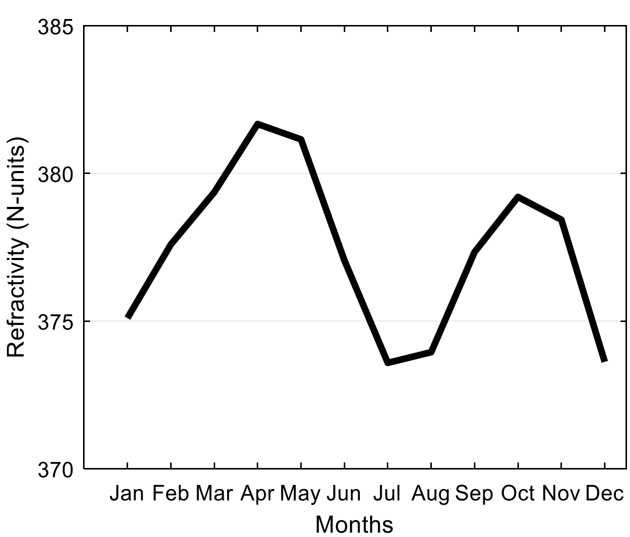

Fig. 2 Average monthly variation of refractivity over freshwater region (January 1979–December 2013)

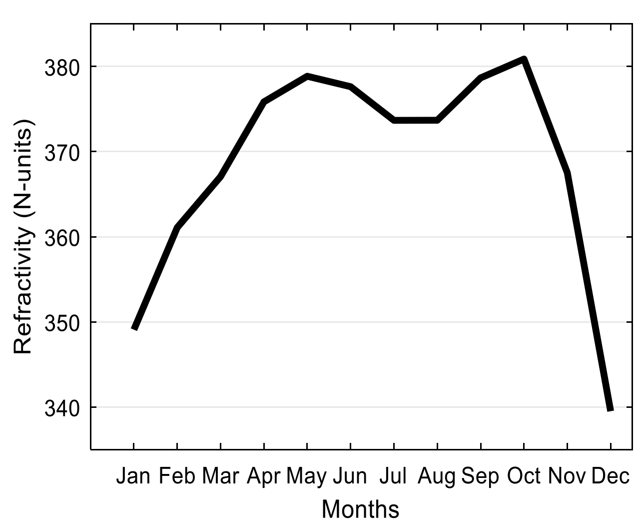

Fig. 3 Average monthly variation of refractivity over rainforest region (January 1979–December 2013)

respectively. The refractivity values in Fig. 3 increase from a minimum value of about 349.09 N units in the month of January to a value of about 378.85 N units in May. It thereafter followed a steady fall till July from which it recorded a slightly uniform value to August before it rose to a peak value of 380.87 N units in October. It further decreases to a minimum value of 339.51 N units in December. This pattern can be attributed to rain pattern in the rainforest region where it usually rain for must part of the year with a short break between July and August. It starts dropping from November with scanty rain before the onset of dry season in December and January. The noticeable decrease observed in Fig. 3 between the month of July and August can also be attributed to the phenomenon of period reduction in rainfall known as August break.

3.3 Average monthly refractivity values over Guinea savannah region

Figure 4 presents the average monthly values of refractivity for 35-year period under study (January 1979–December 2013) over Guinea savannah region. The refractivity values in this region show a pattern with high values of refractivity in the month of April to October which coincided with the period of rainy season. The months of November to March indicate the period of dry season with low values of refractivity. The peak and low values that occurred in the month of September and December has the value of about 375.60 N units and 295.86 N units, respectively. The refractivity value in Guinea savannah region increased from about 300.32 N units in January to about 375.60 N units in September. It thereafter decreases from then to a minimum value of about 295.86 N units in December.

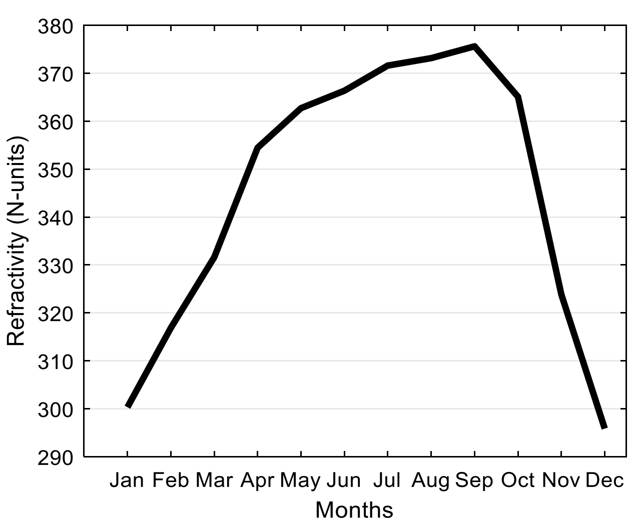

Fig. 4 Average monthly variation of refractivity over Guinea savannah region (January 1979–December 2013)

3.4 Average monthly refractivity values over Sudan savannah region

The average monthly refractivity values for 35-year period under study (January 1979–December 2013) over Sudan savannah region is presented in Fig. 5. Figure 5 indicates that the lowest value of refractivity of about 271.49 N units was seen in February and peak value in August with a value of about 356.06 N units. The value of refractivity increases from a value of about 275.17 N units in January to a minimum value of about 271.49 N units in February. It then increased steadily from March to a peak value of 356.06 N units in August and decreased in December with a value of about 278.23 N units. The high values of refractivity experienced in this region falls between the months of May and September while the low values of refractivity fall in the months of October to April. This pattern can be attributed to seasonal pattern in the Sudan savannah region, Nigeria where a short period of rainfall is experienced.

3.5 Average monthly refractivity values over Sahel savannah region

Figure 6 provides the average monthly values of refractivity for 35-year period under study (January 1979–December 2013) over Sahel savannah region. The refractivity value in this region shows a pattern with high values of refractivity in the months of May to September which also coincided with the rainy season period in Sahel savannah region. The decrease in humidity values between the months of October to April caused the atmosphere to be dry, thereby decreasing the values of refractivity within this period. However, this region experienced peak and lowest values of refractivity in the months of August and March, respectively. The value of

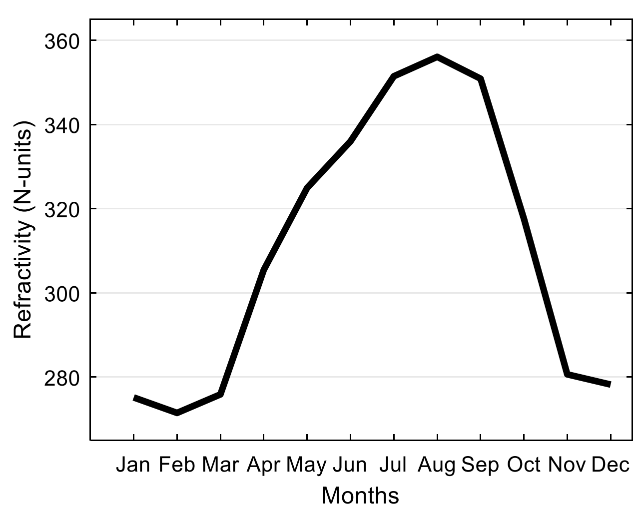

Fig. 5 Average monthly variation of refractivity over Sudan savannah region (January 1979–December 2013)

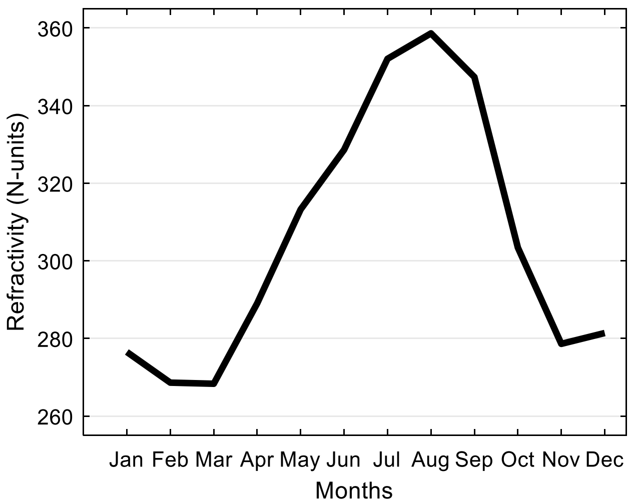

Fig. 6 Average monthly variation of refractivity over Sahel savannah region (January 1979–December 2013

refractivity in Sahel savannah region increases from a value of about 276.50 N units in January and thereafter decreases to a minimum value of about 268.32 N units in March. It then followed a steady increase to a maximum value of about 358.61 N units in August and decreases to December with a value of about 281.39 N units.

It is seen that the decrease in refractivity value between the months of November and December over Rainforest, and October and December over Guinea savannah regions is waterfall-like and over Sudan and Sahel savannah regions it occurred between the months of September to December. This was found different over Freshwater region because of its peculiar nature. Tables 2 and 3 present the average monthly refractivity values and the summary of monthly minimum and maximum refractivity values, respectively, for the vegetation regions.

3.6 Annual average radio refractivity trend over freshwater and rainforest regions

The annual average radio refractivity trend over Freshwater and Rainforest regions for 35-year period (January 1979–December 2013) are depicted in Figs. 7 and 8, respectively. The refractivity trend over Freshwater region, presented in Fig. 7 followed an increasing trend with lowest and highest values of refractivity observed in the year 1986 (374.07 N units) and 2010 (380.69 N units), respectively. While the low values indicated that there was a reduction in rainy season in the year 1986 which caused the humidity values to be low and values of temperature to increase, the high values show heavy rainy season in the year 2010. This simply means that the high humidity and low temperature values enhanced the values of refractivity. Table 4 presents the summary of the result.

The annual radio refractivity trend over Rainforest region as depicted in Fig. 8 also shows an increasing trend for all the period of investigation. Table 5 shows that the highest value of refractivity was observed in the year 2009 (372.37 N units) indicating that this year was the most humid. The lowest value of refractivity was recorded in the year 2000 (363.58 N units).

Table 2 Average monthly refractivity values for the vegetation regions

Month	Freshwater	Rainforest	Guinea Savannah	Sudan Savannah	Sahel Savannah
January	375.10	349.09	300.32	275.17	276.50
February	377.59	361.08	316.87	271.49	268.60
March	379.36	367.07	331.59	275.89	268.32
April	381.67	375.85	354.45	305.46	289.04
May	381.15	378.85	362.71	324.94	313.23
June	377.05	377.63	366.34	335.99	328.61
July	373.58	373.67	371.59	351.45	352.05
August	373.95	373.68	373.14	356.06	358.61
September	377.33	378.66	375.60	350.87	347.36
October	379.20	380.87	365.09	317.61	303.40
November	378.43	367.52	323.82	280.65	278.60
December	373.62	339.51	295.86	278.23	281.39

Table 3 Summary of the minimum and maximum monthly refractivity values of the vegetation regions

	Freshwater	Rainforest	Guinea Savannah	Sudan Savannah	Sahel Savannah
Minimum	373.58	339.51	295.86	271.49	268.32
Maximum	381.67	380.87	375.60	356.06	358.61

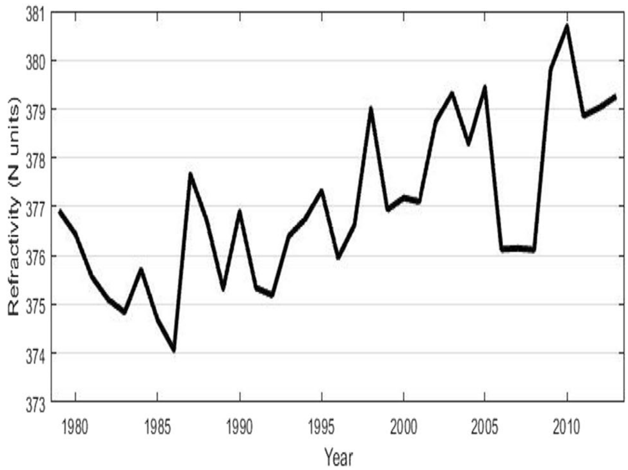

Fig. 7 Annual average radio refractivity trend over freshwater region (January 1979–December 2013)

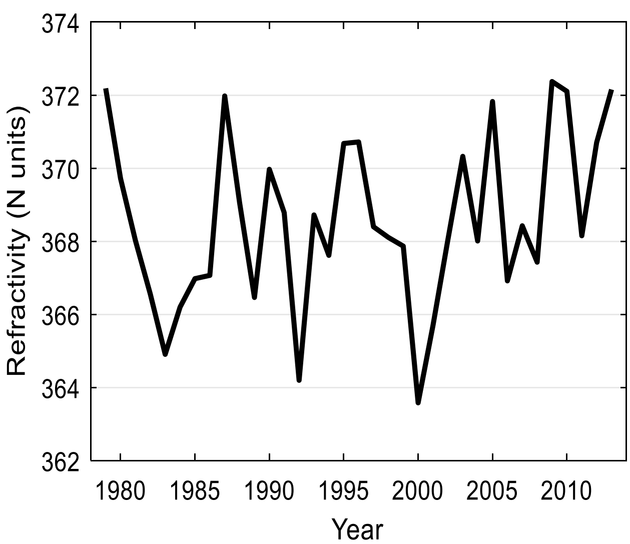

Fig. 8 Annual average radio refractivity trend over rainforest region (January 1979–December 2013)

Table 4 Annual minimum, maximum, mean, standard deviation and rate of change of refractivity values for freshwater region

Year	Minimum	Maximum	Mean	Standard deviation	Annual rate of change
1979	370.33	381.91	376.92	3.19	
1980	370.39	382.56	376.44	3.32	− 0.47
1981	369.43	380.75	375.57	3.59	− 0.88
1982	357.20	381.01	375.10	3.91	− 0.47
1983	355.33	383.43	374.84	5.87	− 0.26
1984	367.73	381.53	375.72	3.43	0.88
1985	367.98	379.97	374.69	3.26	− 1.04
1986	367.06	380.24	374.07	3.75	− 0.62
1987	371.82	381.86	377.66	2.44	3.59
1988	364.28	383.32	376.72	4.85	− 0.94
1989	364.78	381.93	375.32	3.88	− 1.40
1990	369.81	382.69	376.90	3.30	1.58
1991	361.58	381.82	375.34	4.73	− 1.56
1992	366.14	383.38	375.19	4.53	− 0.14
1993	367.08	381.33	376.40	3.22	1.20
1994	368.85	383.42	376.75	3.53	0.35
1995	370.85	384.00	377.33	3.22	0.59
1996	369.32	381.00	375.95	3.26	− 1.38
1997	368.19	382.01	376.63	3.86	0.68
1998	370.05	387.48	379.01	4.53	2.38
1999	370.14	381.74	376.94	3.07	− 2.07
2000	369.48	382.92	377.18	3.70	0.24
2001	366.14	382.88	377.10	4.15	− 0.08
2002	367.66	382.89	378.74	3.22	1.63
2003	372.87	383.97	379.32	2.92	0.58
2004	364.49	384.09	378.29	4.49	− 1.03
2005	367.15	384.40	379.44	3.28	1.15
2006	361.75	381.33	376.13	4.22	− 3.31
2007	365.86	380.46	376.15	3.06	0.02
2008	365.27	380.96	376.12	3.39	− 0.04
2009	375.62	383.43	379.81	1.84	3.69
2010	368.40	387.43	380.69	4.36	0.88
2011	370.98	383.27	378.86	3.11	− 1.83
2012	373.06	384.31	379.03	2.92	0.17
2013	372.44	384.28	379.26	3.02	0.23

3.7 Annual average radio refractivity trend over Guinea, Sudan and Sahel savannah regions

Figures 9, 10, 11 show the annual average radio refractivity trend over Guinea savannah, Sudan savannah and Sahel savannah regions for 35-year period under study (January 1979–December 2013). Figures 9, 10, 11 show a decreasing trend in these regions over all the years investigated. Tables 6, 7 and 8, respectively, show that the highest and lowest values of refractivity within these three regions occurred in the year 1979 and 2000, respectively. The lowest value of refractivity determined in Guinea savannah region, Sudan savannah region and Sahel savannah region was 334.35 N units, 299.41 N units and 295.92 N units, respectively, and the highest value was 350.67 N units, 319.89 N units and 313.34 N units, respectively.

The results show that the pattern of radio refractivity variation in Nigeria is not the same due to different climate characteristics of the country. It is interesting to note that the lowest value of refractivity was observed in the year 2000 in all the regions except in Freshwater region. This may also be attributed to the peculiar nature of this region. The rate of change in refractivity observed within the Freshwater and Rainforest regions, Nigeria is

Table 5 Annual minimum, maximum, mean, standard deviation and rate of change of refractivity values for rainforest region

Year	Minimum	Maximum	Mean	Standard deviation	Annual rate of change
1979	343.30	383.78	372.18	10.37	
1980	341.41	381.27	369.72	10.64	– 2.47
1981	341.87	382.01	368.02	11.61	– 1.70
1982	301.10	380.48	366.55	15.89	– 1.46
1983	300.50	383.58	364.91	17.19	– 1.65
1984	334.66	379.15	366.20	13.27	1.29
1985	338.02	381.29	366.98	12.54	0.78
1986	336.72	379.04	367.07	10.27	0.09
1987	349.19	383.76	371.98	8.59	4.91
1988	315.44	382.02	369.06	15.80	– 2.92
1989	319.47	381.85	366.46	14.55	– 2.60
1990	344.19	380.98	369.97	10.85	3.51
1991	322.37	381.09	368.78	14.96	– 1.19
1992	324.62	380.83	364.20	16.39	– 4.59
1993	326.34	382.80	368.72	13.42	4.52
1994	326.53	382.66	367.62	14.09	– 1.11
1995	348.51	382.78	370.68	9.97	3.06
1996	343.51	380.79	370.72	7.51	0.04
1997	323.95	383.99	368.40	17.44	– 2.32
1998	332.62	384.78	368.11	13.85	– 0.29
1999	338.83	380.02	367.87	10.51	– 0.24
2000	326.10	379.93	363.58	15.71	– 4.29
2001	321.83	380.50	365.70	14.80	2.12
2002	322.15	382.51	368.04	15.14	2.34
2003	340.75	385.23	370.32	11.24	2.28
2004	320.47	383.32	368.01	16.21	– 2.31
2005	330.79	381.59	371.82	7.98	3.82
2006	303.39	384.96	366.92	19.91	– 4.91
2007	317.73	382.62	368.42	15.16	1.51
2008	317.00	384.02	367.43	15.56	– 0.99
2009	345.31	384.08	372.37	11.33	4.94
2010	322.17	385.45	372.10	15.97	– 0.27
2011	325.23	382.70	368.15	17.34	– 3.95
2012	326.83	382.27	370.70	12.77	2.55
2013	332.30	384.06	372.15	11.57	1.45

$\left(\frac{dN}{dy}\right) = 0.1$ N units year^{-1} and for the Guinea savannah, Sudan savannah and Sahel savannah regions, Nigeria is $\left(\frac{dN}{dy}\right) = -0.1$ N units year^{-1}. The results revealed that the decreases in refractivity per year in the dry climates (north of the Nigeria) is 0.1 N units year^{-1} while the Rainforests (south of the Nigeria) increases by 0.1 N units year^{-1}. These changes could be attributed to gradual changes in the climate, especially since these values represent mean aggregated changes over periods of more than 30 years.

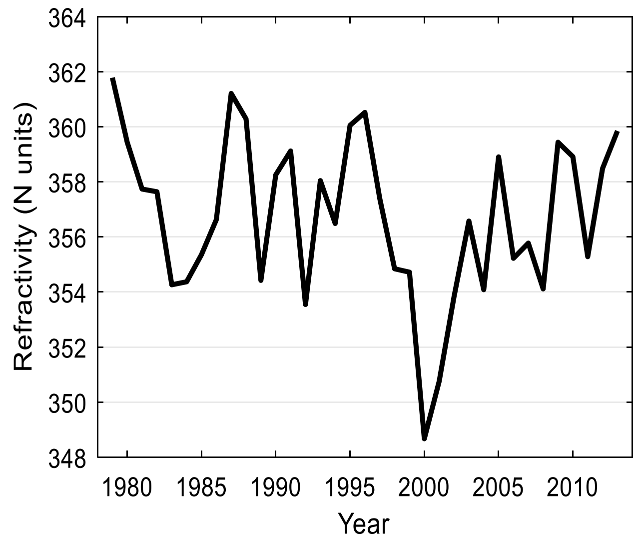

Fig. 9 Annual average radio refractivity trend over Guinea savannah region (January 1979–December 2013)

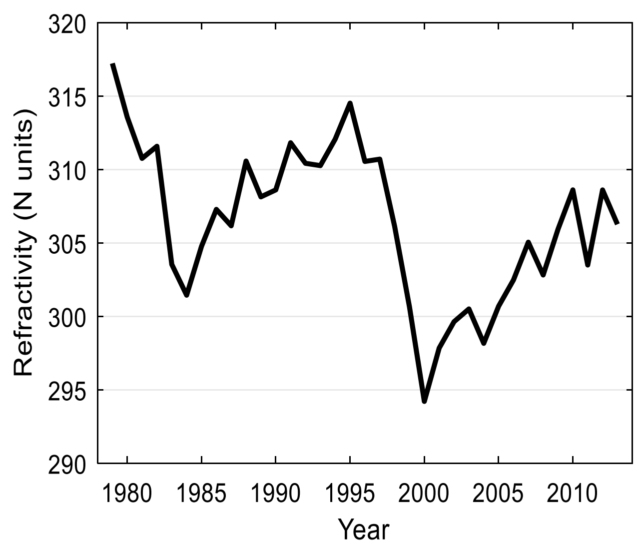

Fig. 10 Annual average radio refractivity trend over Sudan savannah region (January 1979–December 2013)

3.8 Comparison of annual average radio refractivity trend between different vegetation regions

Figure 12 presents the comparison of the annual average refractivity trend between different vegetation regions investigated for 35-year period (January 1979–December 2013). It is interesting to observe from virtual inspection that all the vegetation regions show a patternless behavior from year to year over the 35-year period under consideration as presented in Fig. 12. It is also interesting to see from Fig. 12 that while refractivity values are high for the Freshwater

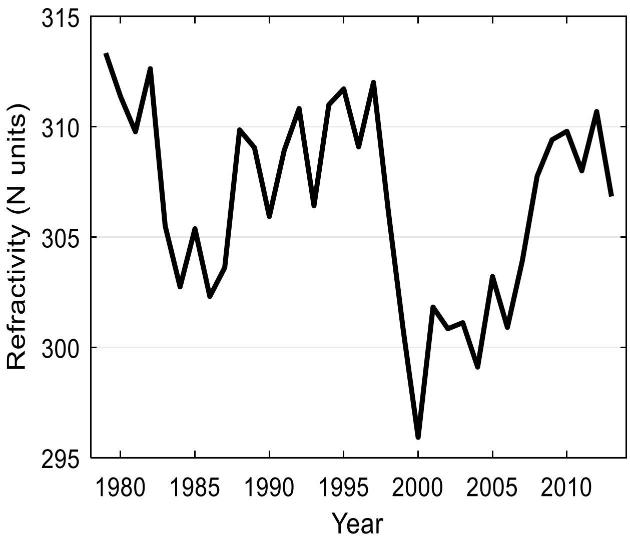

Fig. 11 Annual average radio refractivity trend over Sahel savannah region (January 1979–December 2013)

and Rainforest regions, the values are low for the Sudan and Sahel savannah regions, and the values for the Guinea savannah region come in between the two extremes. This observation can be explained to be due to the high humidity values experienced at the Freshwater and Rainforests regions (leading to high refractivity values) and the low humidity values experienced at the Sudan and Sahel savannah regions (leading to low refractivity values). The Guinea savannah region is geographically located between these two sets of regions, and so the moderate values of refractivity observed for the region.

4 Conclusion

The study has investigated the tropospheric radio refractivity trend over vegetation regions in Nigeria. The five vegetation regions we considered including their states are Bayelsa and Rivers (Freshwater); Imo, Osun and Ondo (Rainforest); Kwara, Abuja and Niger (Guinea savannah region); Adamawa, Bauchi and Sokoto (Sudan savannah region); Yobe and Borno (Sahel savannah region), for the period of 35 years investigated (January 1979–December 2013). The meteorological parameters we used to calculate the refractivity were temperature, relative humidity and pressure. The results revealed that the highest and lowest values of refractivity in Freshwater region occurred in the year 1986 and 2010, respectively. In Rainforest region, the lowest and highest values of refractivity were observed in the year 2000 and 2009, respectively. While in savannah regions (Guinea, Sudan and Sahel) the highest and lowest values of refractivity occurred in the year 1979 and 2000, respectively.

Table 6 Annual minimum, maximum, mean, standard deviation and rate of change of refractivity values for Guinea savannah region

Year	Minimum	Maximum	Mean	Standard deviation	Annual rate of change
1979	293.68	378.57	350.67	29.30	
1980	294.35	378.19	348.84	28.20	− 1.83
1981	293.53	378.79	347.05	29.97	− 1.78
1982	282.74	377.79	346.03	30.97	− 1.02
1983	283.08	374.02	342.29	27.58	− 3.74
1984	285.32	369.19	340.56	26.97	− 1.73
1985	287.69	376.48	343.59	29.45	3.03
1986	292.11	375.39	346.40	25.26	2.81
1987	294.75	378.73	348.61	26.07	2.21
1988	279.80	377.35	348.19	27.82	− 0.41
1989	279.15	377.28	344.28	29.57	− 3.92
1990	297.66	376.59	346.74	27.26	2.46
1991	288.22	377.05	348.45	28.14	1.72
1992	287.26	374.26	343.01	31.39	− 5.44
1993	291.50	377.06	347.94	26.56	4.93
1994	290.49	379.47	346.16	29.88	− 1.78
1995	292.09	379.38	349.69	28.99	3.53
1996	293.86	376.60	348.98	25.44	− 0.71
1997	281.90	377.82	345.69	32.68	− 3.29
1998	285.06	377.89	341.68	31.83	− 4.02
1999	285.80	376.11	341.18	26.82	− 0.49
2000	281.51	366.19	334.35	29.83	− 6.84
2001	277.41	370.74	336.39	30.02	2.04
2002	279.13	373.86	341.25	29.59	4.86
2003	285.84	378.62	341.98	29.37	0.73
2004	282.48	373.22	340.76	30.94	− 1.22
2005	291.57	376.28	344.63	24.91	3.87
2006	281.34	380.77	342.92	31.31	− 1.71
2007	281.72	379.19	343.32	30.98	0.40
2008	281.01	378.49	340.76	30.23	− 2.56
2009	288.09	379.01	346.26	29.02	5.50
2010	285.98	379.84	346.75	30.68	0.50
2011	285.31	376.66	342.63	29.86	− 4.12
2012	286.40	376.97	346.64	27.41	4.01
2013	281.56	376.36	346.86	26.28	0.22

The annual mean refractivity trend revealed that the rate of decreases in refractivity per year in the savannah regions (Guinea, Sudan and Sahel) of Nigeria is 0.1 N units year^{-1}, while in Freshwater and Rainforest regions of Nigeria, refractivity increases by 0.1 N units year^{-1}. We concluded that the changes could be attributed to gradual changes in the climate, especially since these values represent mean aggregated changes over periods of more than 30 years. This evidence shows that tropospheric radio refractivity increases from the savannah regions to Freshwater regions in Nigeria. The result from comparison

Table 7 Annual minimum, maximum, mean, standard deviation and rate of change of refractivity values for Sudan savannah region

Year	Minimum	Maximum	Mean	Standard deviation	Annual rate of change
1979	301.65	336.98	319.89	35.54	
1980	270.99	362.49	316.17	34.42	– 3.72
1981	271.64	362.71	314.91	34.53	– 1.26
1982	271.97	361.06	315.72	32.84	0.81
1983	267.64	355.09	307.34	32.86	– 8.38
1984	267.34	347.94	306.35	28.87	– 0.99
1985	264.41	359.71	308.95	32.93	2.60
1986	268.61	357.63	309.75	30.51	0.81
1987	268.18	361.65	309.09	33.84	– 0.67
1988	269.09	364.78	314.06	34.28	4.97
1989	269.01	363.71	311.17	34.31	– 2.89
1990	267.49	358.63	311.71	31.60	0.55
1991	272.69	361.45	313.62	31.94	1.91
1992	267.86	358.56	312.52	31.44	– 1.10
1993	270.01	359.09	312.21	31.16	– 0.32
1994	267.45	363.46	313.70	33.76	1.50
1995	272.75	364.50	316.83	33.89	3.13
1996	271.20	361.72	313.60	33.85	– 3.23
1997	270.40	359.03	314.35	33.34	0.74
1998	266.91	358.43	308.88	33.92	– 5.47
1999	267.34	355.34	305.48	30.56	– 3.40
2000	265.26	341.89	299.41	27.16	– 6.06
2001	265.53	353.14	303.01	31.32	3.59
2002	268.31	350.47	304.02	30.08	1.02
2003	265.27	355.83	305.56	32.38	1.54
2004	265.87	350.88	303.89	29.24	– 1.67
2005	268.53	354.05	306.78	31.47	2.89
2006	265.29	359.48	306.68	33.10	– 0.10
2007	265.30	360.03	309.43	32.57	2.75
2008	268.65	359.05	308.85	32.43	– 0.58
2009	267.72	360.43	312.44	33.83	3.59
2010	269.09	362.30	313.70	34.31	1.26
2011	271.72	359.66	310.56	31.97	– 3.14
2012	268.65	361.38	314.26	32.74	3.69
2013	271.16	358.93	313.53	29.58	– 0.72

Table 8 Annual minimum, maximum, mean, standard deviation and rate of change of refractivity values for Sahel savannah region

Year	Minimum	Maximum	Sah mean	Standard deviation	Annual rate of change
1979	269.98	366.87	313.34	34.12	
1980	270.29	364.42	311.32	32.27	– 2.02
1981	266.29	363.06	309.77	33.93	– 1.55
1982	271.79	365.25	312.63	34.19	2.86
1983	264.94	363.64	305.50	35.06	– 7.13
1984	266.59	348.07	302.74	27.73	– 2.76
1985	267.02	359.70	305.38	32.78	2.64
1986	264.09	356.66	302.30	31.99	– 3.07
1987	262.82	364.28	303.61	33.58	1.31
1988	264.69	368.49	309.86	34.93	6.25
1989	266.69	364.40	309.05	33.47	– 0.80
1990	269.26	359.10	305.93	30.10	– 3.12
1991	269.95	363.75	308.93	30.92	2.99
1992	272.12	362.86	310.83	30.63	1.90
1993	266.80	359.00	306.42	30.03	– 4.41
1994	265.18	370.56	311.00	34.59	4.58
1995	271.64	366.14	311.72	34.84	0.72
1996	269.31	367.05	309.09	34.98	– 2.63
1997	272.71	360.98	312.01	31.58	2.93
1998	266.28	363.85	306.15	33.84	– 5.86
1999	261.33	360.23	300.78	32.94	– 5.37
2000	262.51	343.22	295.92	26.68	– 4.86
2001	262.00	359.35	301.82	30.55	5.91
2002	264.08	356.82	300.84	30.67	– 0.98
2003	265.07	360.30	301.12	33.25	0.27
2004	264.21	352.74	299.10	29.36	– 2.01
2005	261.69	362.62	303.21	33.76	4.11
2006	261.15	351.83	300.90	28.78	– 2.31
2007	265.08	365.02	303.92	31.77	3.01
2008	265.18	369.32	307.76	34.99	3.84
2009	265.23	360.24	309.41	32.13	1.65
2010	265.45	367.31	309.79	35.66	0.38
2011	266.45	366.16	308.00	34.88	– 1.80
2012	268.55	368.94	310.69	35.31	2.69
2013	264.16	366.21	306.84	33.68	– 3.85

trend revealed that Guinea savannah region stands between Freshwater and Rainforest regions and Sudan and Sahel savannah regions.

In overall, the study contributes a more in-depth understanding of the tropospheric radio refractivity trend over Nigeria vegetation regions which depends on meteorological parameters such as temperature, relative humidity and pressure. The results from our study can be utilized by the communication and broadcasting industries to enhance their design of communication systems for Nigeria environment.

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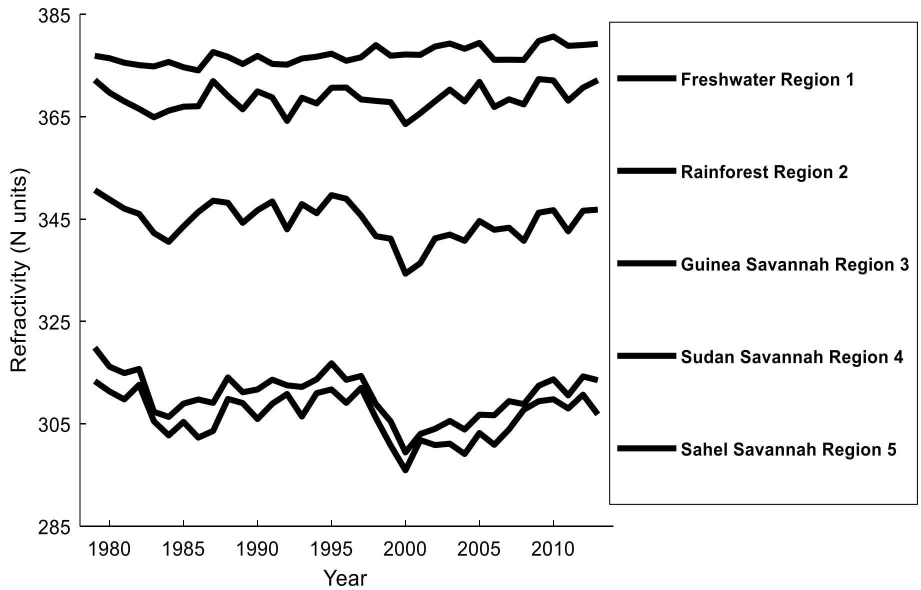

Fig. 12 Comparison of the annual average radio refractivity trend between different vegetation regions

Data availability Data used in this study are available from the web archive of the ERA-Interim data of the European Centre for Medium-Range Weather Forecasts (ECMWF; website: https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/). The data were obtained in NETCDF file format, and the MATLAB function "ncread" was used to extract data from the files.

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