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Refractivity Gradient Variations and Intertropical Discontinuities Across Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The complexity of the troposphere has a significant impact on radio signal transmission. This has led to the computation of refractivity gradients, which is an important parameter for the estimation of path clearance and propagation effects such as super-refraction, sub-refraction and ducting. This research focuses on the interrelationships that exist between Refractivity Gradient and Intertropical Discontinuity (ITD). The ITD is a major phenomenon that determines weather in West Africa. Refractivity gradient was calculated using hourly data of temperature and relative humidity for the years 2017and 2018 taken at two levels (surface and 1000hpa) collected from the archives of the European Centre for Medium-Range Forecasts (ECMWF) for twenty meteorological stations in Nigeria. The refractivity gradient values obtained were used to characterize the atmospheric conditions of the stations diurnally and seasonally. Results showed that during the dry season, the atmosphere is sub-refractive at the coastal and derived savannah regions while during the rainy season super-refractive conditions prevails. At the guinea and sub-Sahelian regions the atmosphere is mostly sub-refractive. Diurnal variations show that the coastal and derived savannah regions have atmosphere that are super refractive throughout the day, the guinea savannah

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regions are characterized by atmosphere that is super-refractive in the early morning hours and sub-refractive between late morning and afternoon periods. These occurrences are found to be greatly influenced by the north-south trajectory of the Intertropical Discontinuity.

Keywords: Refractivity gradient; intertropical discontinuity; phenomenon; diurnal.

1. INTRODUCTION

The relationship between surface refractivity, refractivity gradient, and radio refractivity is complex and interconnected. Surface refractivity refers to the refractive index observed at the Earth's surface, which is influenced by various atmospheric conditions such as temperature, pressure, and humidity [1]. On the other hand, the refractivity gradient measures the vertical change in refractivity with respect to height in the atmosphere [2,3]. Fluctuations in atmospheric conditions can affect the refraction of radio waves, which in turn influences radio refractivity [4,5].

The combination of surface refractivity and refractivity gradient collectively determines total radio refractivity, which plays a crucial role in the propagation characteristics of radio waves in the atmosphere. Changes in surface refractivity and refractivity gradient can induce fluctuations in radio refractivity, leading to variations in signal propagation, fading, and interference in wireless communication systems [6-8].

Numerous scientific studies have investigated the correlation between surface refractivity, refractivity gradient, and radio refractivity in different scenarios [9-11]. Akpootu and Rabiu [12] developed empirical models to estimate tropospheric radio refractivity in Osogbo, Nigeria, considering atmospheric variables such as pressure, humidity, and temperature. Dairo et al. (2020) examined the impact of tropospheric scintillation on satellite links across different climatic zones in Nigeria, where the refractivity gradient plays a role.

Abnormal propagation conditions, such as multipath fading and significant signal enhancement on line-of-sight links, or interference on trans-horizon paths, can be better identified using the spatial distribution of vertical refractivity gradient and ducting index [13]. These abnormal conditions can result in decreased signal strength, reduced reliability, and degraded quality of wireless communication.

When designing radio systems, the radio refractivity gradient is a crucial parameter to consider. Strong negative gradients, known as super-refraction, can cause interference between terrestrial stations, while positive gradients, known as sub-refraction, can affect the lowest detectable signal level. Understanding the distribution and variability of the surface refractivity gradient is essential for optimal performance in radio systems [14-16].

The Intertropical Discontinuity (ITD) serves as a transition zone between humid maritime air masses and dry continental air masses [17-19]. It is characterized by a significant gradient in atmospheric variables such as temperature, humidity, and refractivity [20,21]. The movement of the ITD affects the unpredictability and intensity of the "Little Dry Season" in southern Nigeria, as it is related to variations in rainfall patterns [22-25]. The ITD acts as a barrier between the humid maritime air mass and the continental air mass of the Harmattan [26].

The intertropical discontinuity contributes to the formation of the refractivity gradient due to temperature and humidity variations. Research conducted by Dairo et al. [27] used radiosonde data to investigate the refractivity gradient across the ITD. The refractivity gradient is more pronounced in areas influenced by the intertropical discontinuity zone due to significant temperature and moisture content differences among trade wind systems [28-30].

The intertropical discontinuity also affects radar systems operating in tropical regions through its influence on the refractivity gradient. López et al. [31] conducted research on the impact of the ITD on the performance of weather radar. They found that fluctuations in the refractivity gradient over the ITD can introduce errors into radar data, affecting the accuracy of rainfall estimation and storm tracking.

2. METHODOLOGY

Temperature and relative humidity readings were collected hourly at the surface and at a height of 1 km with an equivalent pressure of 1000 hpa during the course of two (2) years of Era

Interim data collection (2017-2018). These data, which had a resolution of 0.25x0.25, were obtained from the archives of the European Centre for Medium-Range Forecasts (ECMWF). They were used for this research, and they were dispersed over twenty stations that were located in each of Nigeria's four climatic areas: the Coastal, Derived, Guinea, and Sub-Sahel regions.

To deduce the position of ITD (Intertropical Discontinuity) mean monthly locations across Nigeria, the dewpoint temperature readings were collected at the same height and with the same resolution for all of the readings.

2.1 Data and Data Analysis Technique

For the purpose of estimating the radio refractivity gradient, of the lowest 1 km of the troposphere, the data was group such that between the surface and 1 km was classified as the lowest 1 km. The value of radio refractivity was computed from equation 2.1. The refractivity gradient data of the lowest atmospheric layers within the range of 0-1 km, ΔN_{1km}, were computed using equation (2.2). The value of the radio refractivity gradient obtained were used to characterize the refractive propagation conditions of the lowest atmosphere into sub-refraction $\left(\frac{\Delta N}{\Delta h} > -40\right)$, super-refraction $\left(\frac{\Delta N}{\Delta h} > -157 < -40\right)$, and ducting $\left(\frac{\Delta N}{\Delta h} < -157\right)$. The refractivity gradient value is thus presented in the results and discussion.

The variation of refractivity gradients (dN) is a function of climate, season, and transient weather conditions across the day and terrain over the communication path [32]. Negative value of refractivity gradients (beyond 100 N-unit/km) cause the radio signal to bend toward the earth and to traverse beyond the geometric horizon (super-refraction). When it becomes positive, it is known as sub-refraction and can cause diffraction loss [33].

Fig. 1. Map of the study location

The Refractivity (N) which is the physical property of a medium as determined by its index of refraction is denoted by;

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

The refractive index of air, denoted as n, exhibits a deviation from unity that is limited to a small fraction of a few parts per ten thousand [34].

The radio refractivity, denoted as (N) as recommended by ITU, is determined by the combined dry and wet parametric values, and may be mathematically represented as;

$$N = 77.6\frac{P}{T} + 3.73X10^5\frac{e}{T^2} \text{ (N-units)} \quad (2.1)$$

Equation (1) above is divided into two parts

$$N = N_{DRY} + N_{WET} \quad (2.2)$$

where,

$$N_{DRY} = 77.6\frac{P}{T}$$

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

where,

- P= atmospheric pressure (hpa),
- e = water vapour pressure (hpa),
- T= absolute temperature (K)

The differential equation that describes the relationship between the water vapour pressure, e (hPa), the saturation vapour pressure, es (hPa), and the relative humidity, H (%), may be derived from equation (2.1) as follows:

$$e = \frac{H}{100}es \quad (2.3)$$

where,

$$es = a\exp\left[\frac{bt}{t+c}\right] \quad (2.4)$$

The values of the coefficients in equation (2.4) are obtained as a = 6.1121, b = 17.502, c = 240.97. The atmospheric temperature, denoted as T, is measured in Kelvin (K), whereas the dry atmospheric pressure, represented by P in (hPa). Additionally, the temperature, denoted as t in (°C).

Hence, the Refractivity Gradient in N-units per km may be represented as:

$$G = \frac{dN}{dh} = \frac{N_{1km} - N_s}{\Delta h} \quad (2.5)$$

Where N_{1km} is the refractivity at 1 km height is, N_s is the refractivity at the surface, Δh is change in height.

The connection between the Latitudinal (L) location of the Intertropical discontinuity (ITD), which is the independent variable, and the Refractivity Gradient (RG), which is the dependent variable, was investigated using five regression models in this work.

3. RESULTS AND DISCUSSION

3.1 Spatial Distribution of Refractivity Gradient Across Nigeria

3.1.1 Late dry season period

The seasonal variations of the radio refractivity gradient is presented in Fig. 2 which shows the Late dry season months of (December - February) which is dominated by very little rainfalls, the results obtained indicated variations at the different stations, having their maximum values at the Sahel regions indicating sub-refractions with positive values ranging from (25.704 – 105.8) The values are lesser in the coastal regions which is dominated by super-refractions, the guinea savanna regions such as minna, bida, jos are partly sub-refractive and super refractive while the derived regions such as Ilorin, Abeokuta are significantly dominated by super refractions for the period of December-February.

3.1.2 Early rainy season

The seasonal variation of radio refractivity gradient is presented in Fig. 3, as we move inland the values of refractivity gradient increases. The Coastal and derived savannah region were super-refractive due to high level of humidity in the atmosphere as a result of rainfall, while the Guinea and Sahel savannah region were sub-refractive as a result of low amount of humidity attributed to very low rainfall in these regions at the early raining season months.

3.1.3 Late rainy season

The atmosphere across Nigeria during this period is Super-refractive as shown in Fig. 4 due to the rainfalls that dominated the nation around this period. The values of refractivity gradient increases as we move from south to north across the Nation.

3.1.4 Early dry season

The atmosphere in the coastal and derived regions was Super-refractive in this period which can be attributed to the humid atmosphere and the influence of the water bodies present around these regions. The reverse is the case in the Guinea savanna and Sub-Sahelian regions which were Sub-refractive as shown in Fig. 5 with an exception of Kano which was super-refractive, the presence of water bodies such as Jakara River and Kusalla dam in this area seems to be the major reason why the atmosphere here was super-refractive.

3.2 Inter Connection between Refractivity Gradient and Intertropical Discontinuity

The climate of the Earth is not dependent on the fact that sunlight is evenly distributed around the equator. Climatic irregularities are significant in the eastern tropical Pacific and Atlantic Oceans where the regions of maximum sea surface temperature, convective cloud cover, and rainfall

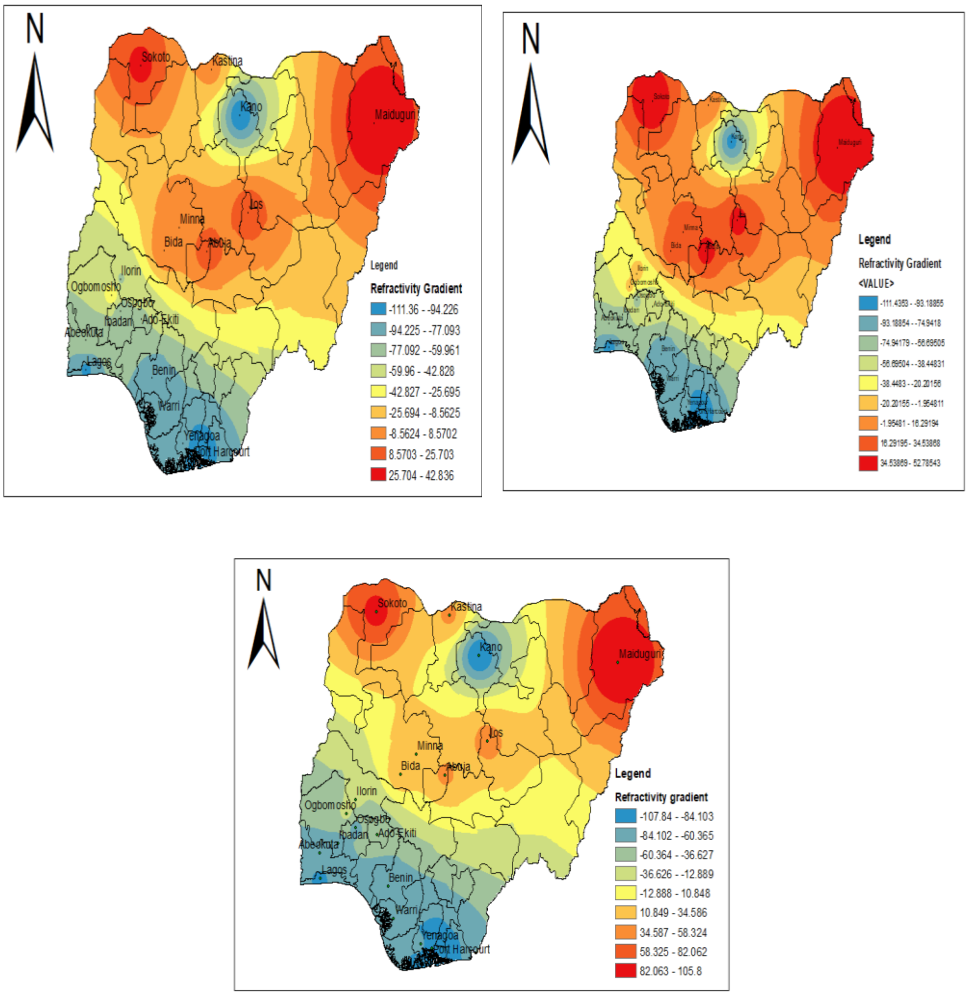


Fig. 2. Spatial distribution of Refractivity Gradient across Nigeria in the late dry season of December, January and February

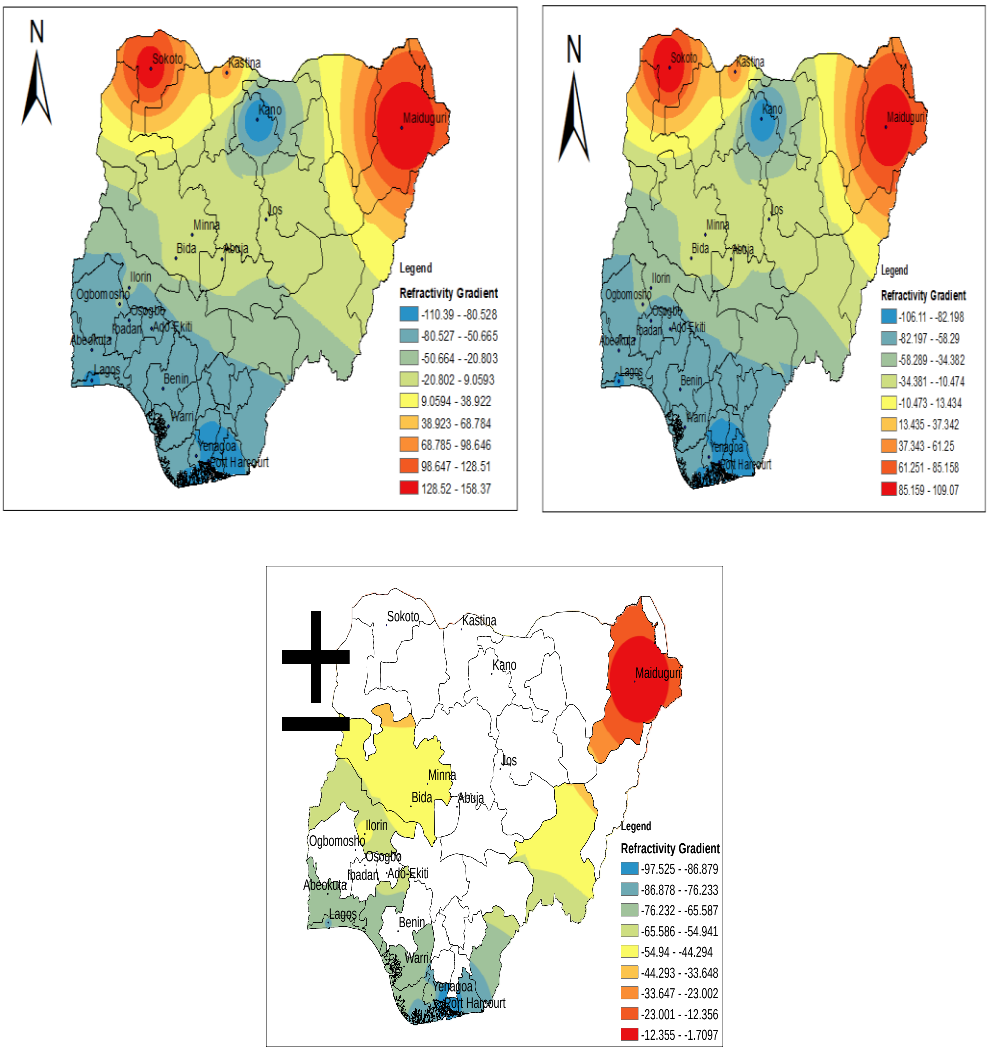
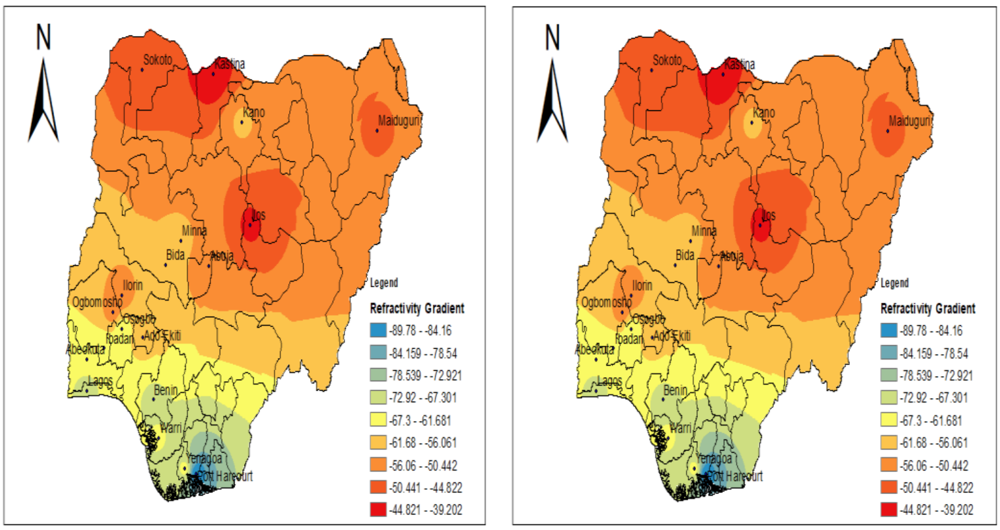


Fig. 3. Spatial distribution of Refractivity Gradient across Nigeria in the early rainy season of March, April and May



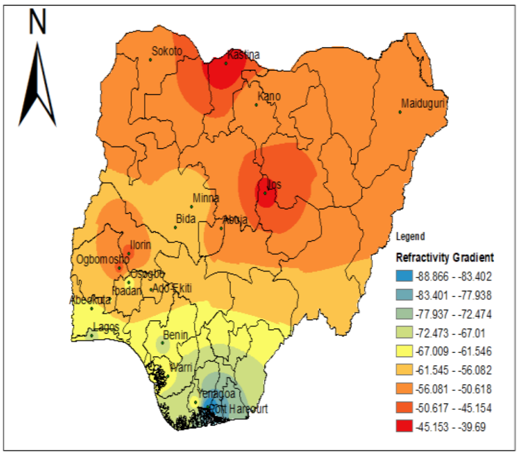


Fig. 4. Spatial distribution of Refractivity Gradient across Nigeria in the late Rainy season of June, July and August

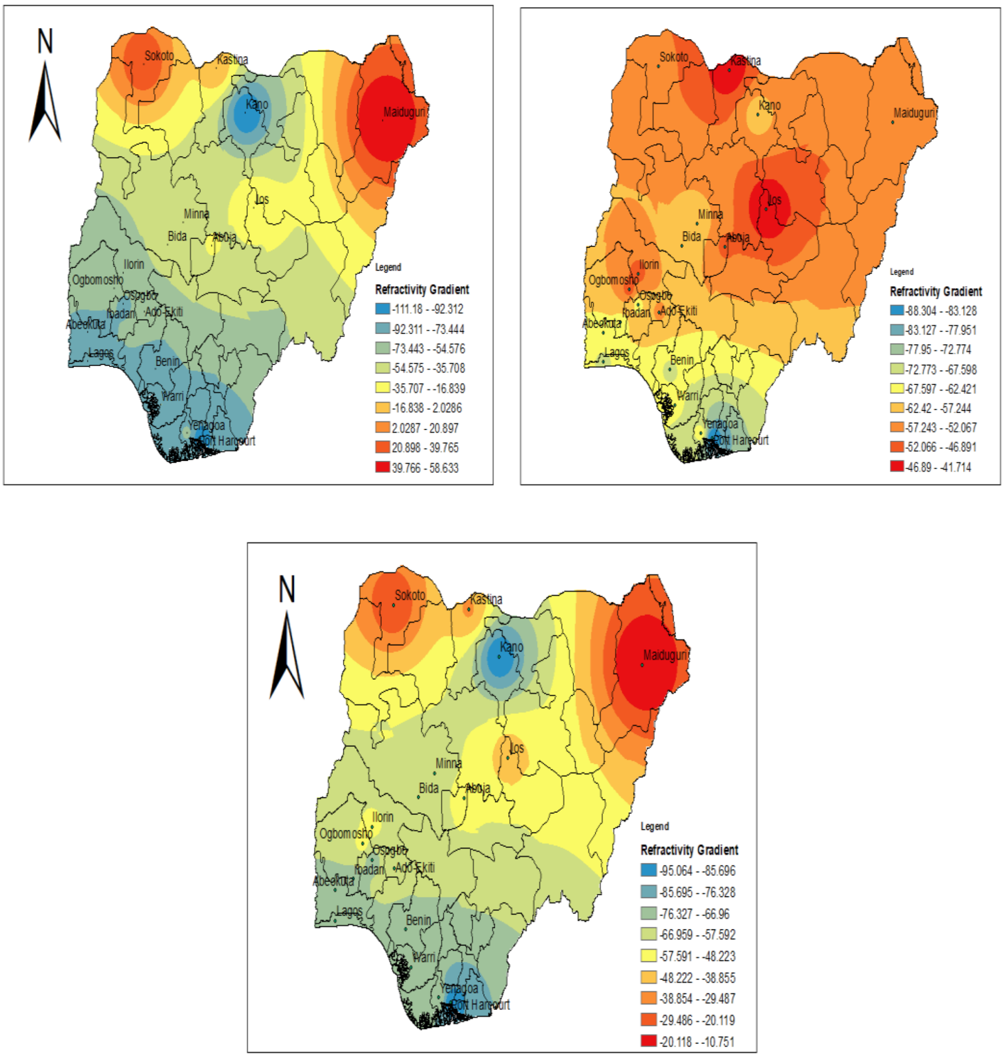


Fig. 5. Spatial distribution of Refractivity Gradient across Nigeria in the Early dry season of September, October and November

occur north of the equator. This is the result of two sets of factors: interactions between the ocean and atmosphere that are capable of convening balance into imbalance, and the geometries of the continents that determine in which longitudes the interactions are effective and in which hemisphere the warmest waters and the intertropical discontinuity is located. Where the transition zone is shallow, winds can easily impact the sea surface temperature, making for optimal ocean-atmosphere interactions. The convective shoreline in the tropical Atlantic and Pacific to the east, but not in the Indian Ocean, since the former is dominated by easterly trade winds and the latter by monsoons, which have a much bigger meridional component.

3.2.1 January-February

In January-March, the seasonal variation of radio refractivity gradient is presented along with the Intertropical discontinuity (ITD) for the month of January. The position of ITD, covers the coastal and a large part of the derived regions at about (366-377) km as shown in Fig. 6 below, even though January to February is known to be a dry month, it can be deduced that little amount of rainfall can still be experienced in the coastal and derived regions. The atmosphere in the coastal and derived regions in this month was super-refractive while regions above ITD were sub-refractive.

3.2.2 March – April

In April, the position of ITD as shown below, shifted further north covering the coastal, derived Guinea savannah at an altitude of (544 - 777) km. This month was majorly characterized with heavy rainfalls all over the regions covered by the ITD position as shown below in Fig. 7; the coastal, derived and Guinea savannah regions remains super-refractive. The sub-Sahelian region was sub-refractive

3.2.3 May - June

ITD position shifted above Nigeria, cutting through a fraction of the Sub-Sahelian region over the land through Yobe and Borno in the month of May and disappeared completely in June as shown below in Fig. 8 at about an altitude of (1,166 -1,388) km; this implies that all stations across Nigeria will experience rainfall. All regions were super-refractive during this period.

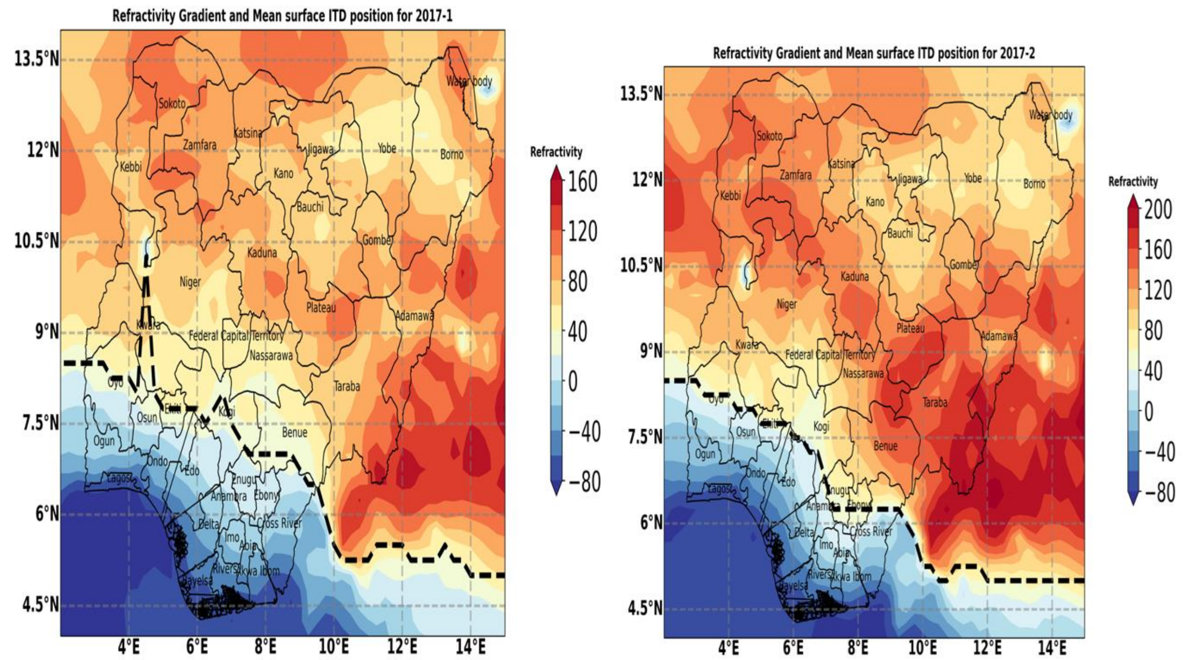


Fig. 6. Refractivity Gradient and mean surface ITD position for 2017-1 and 2017-2

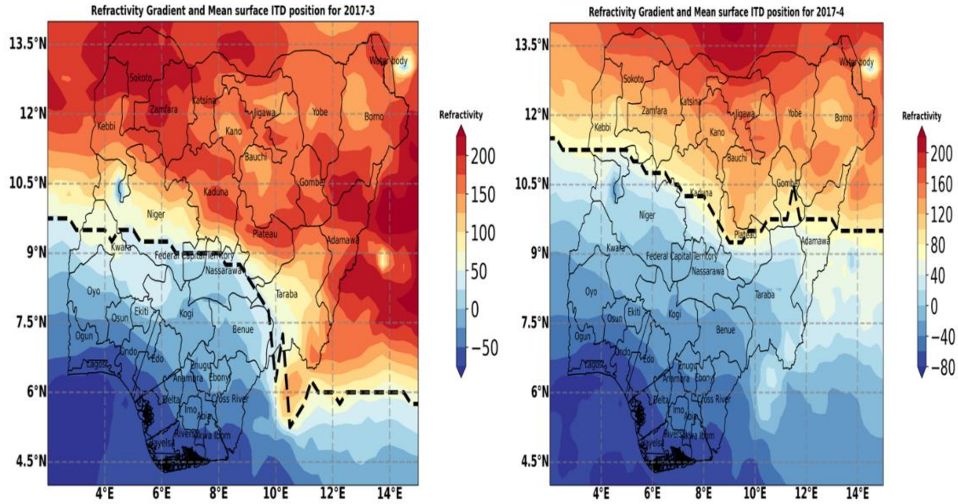


Fig. 7. Refractivity Gradient and mean surface ITD position for 2017-3 and 2017-4

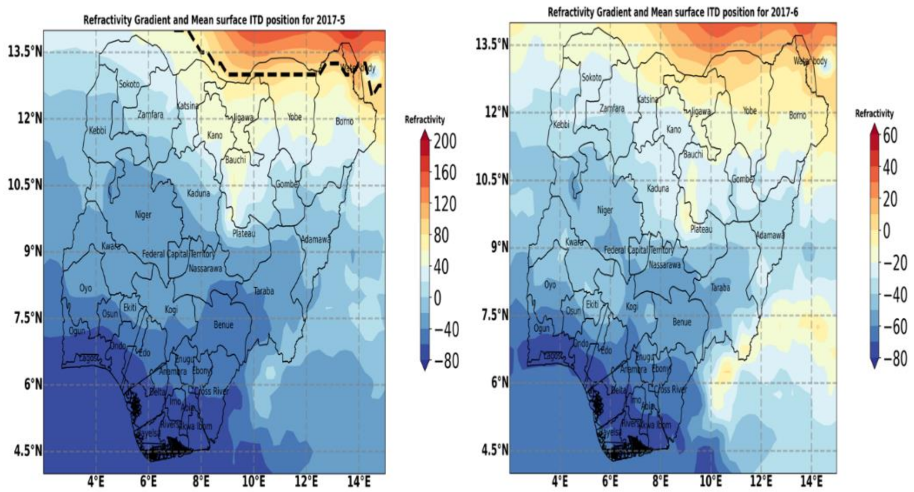
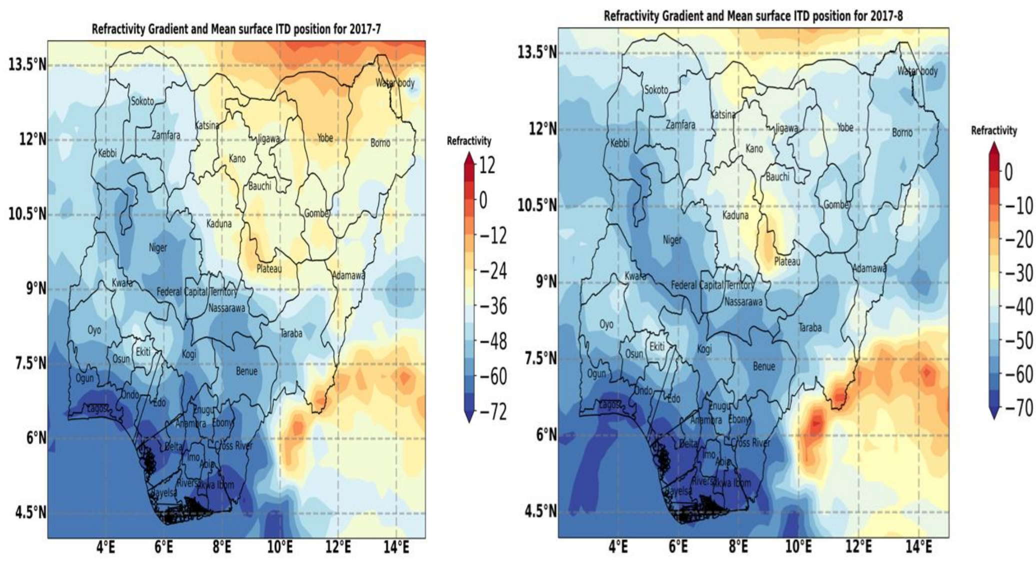


Fig. 8. Refractivity Gradient and mean surface ITD position for 2017-5 and 2017-6



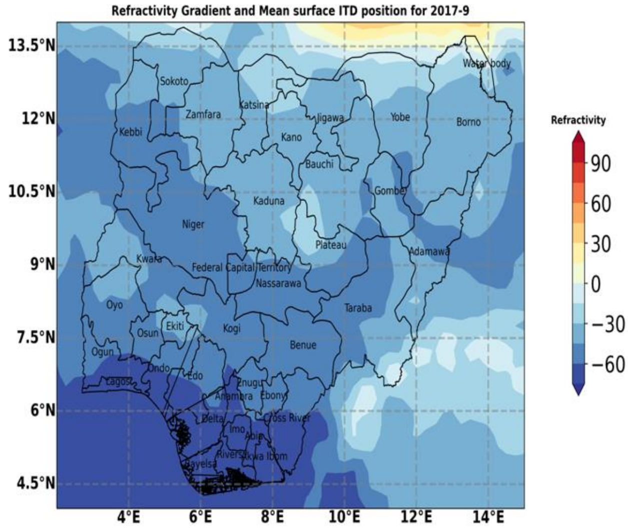


Fig. 9. Refractivity Gradient and mean surface ITD position for 2017-7, 2017-8 and 2017-9

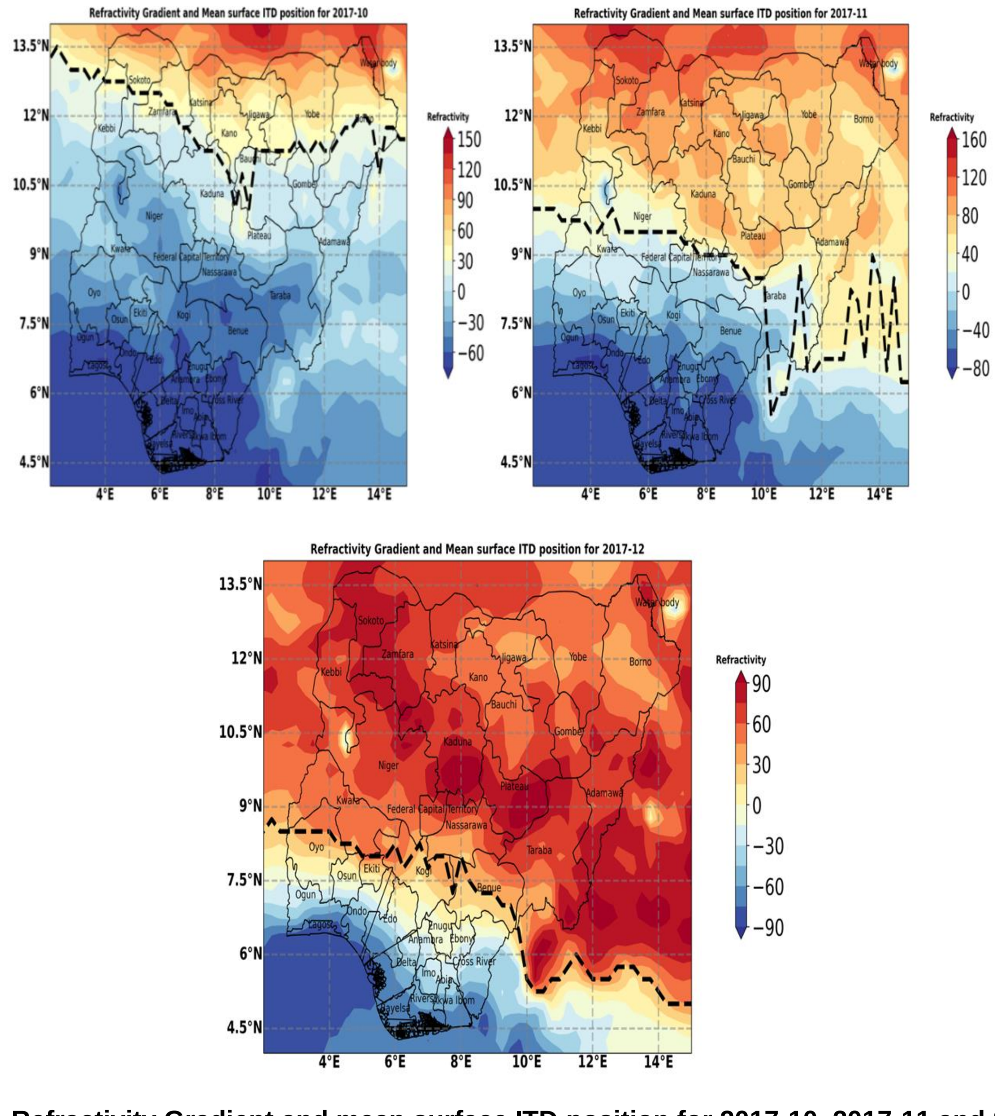


Fig. 10. Refractivity Gradient and mean surface ITD position for 2017-10, 2017-11 and 2017-12

3.2.4 July-September

From July-September, the position of ITD still remains above Nigeria, which indicates the presence of rainfall all over Nigeria as shown below in Fig. 9 at an altitude of (1,476 – 1,598) km, the values of refractivity in this period increases over the northern part of the nation. The atmosphere remains super-refractive around this period due to continuation of rainfall experienced from the month of May to June.

3.2.5 October-December

In the month of November, ITD position shifted further south of Nigeria retuning back after its disappearance in the month of may at an altitude of (966-411) km as shown below in Fig. 10, regions above the line remains super-refractive while those above were sub-refractive.

4. CONCLUSION

The relationship between refractivity gradients and intertropical discontinuities has been convincingly demonstrated in this work, with differences in refractivity gradients found to be very low during wet seasons and large during dry seasons across all stations, with stations near the coast having lower refractivity values than other stations due to their proximity to the ocean. The movement of the intertropical discontinuity (ITD) across all stations has indicated an impact on rainfall distribution across all stations. As the latitudinal position of ITD grows, the value of the refractivity gradient decreases throughout the stations.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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