

Temporal Variability and Meteorological Controls of Radio Refractivity over Lagos, Nigeria, 1995-2024

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Abstract: This study investigates the temporal variability and meteorological controls of surface radio refractivity over Lagos, Nigeria, using monthly temperature, pressure, and vapour pressure observations from 1995–2024. Radio refractivity and its dry and wet components were calculated using the standard ITU-R formulation. Descriptive statistics, component variance decomposition, temperature-pressure cross-correlation, and linear, quadratic, and cubic regression analyses were used to characterise the refractivity series. The mean refractivity was 376.79 N-units, with the dry and wet components contributing 68.6% and 31.4%, respectively. Despite its smaller contribution to the mean, the wet component accounted for 109.42% of temporal variance, compared with 5.43% for the dry component, while covariance contributed –14.85%. Temperature and pressure showed a strong inverse zero-lag correlation $r = -0.894$. The linear trend was weak ($-0.022 \text{ N-units yr}^{-1}$; $R^2 = 0.000649$), with negligible improvement from higher-order polynomial models. The work explicitly distinguishes between the components controlling mean refractivity and those controlling its temporal variability, demonstrating that atmospheric moisture is the dominant driver of refractivity fluctuations over Lagos despite the dominance of the dry component in the mean state.

Keywords: radio refractivity; atmospheric moisture; temporal variability; variance decomposition; tropospheric propagation

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1.0 Introduction

The reliable propagation of radio waves through the lower atmosphere is essential to the performance of modern wireless communication and navigation systems. Mobile telecommunications, broadcasting, satellite communication, aviation, and other radio-based services depend on the predictable transmission of electromagnetic waves through the atmosphere. However, atmospheric conditions can substantially modify radio-wave propagation, particularly within the troposphere, where variations in temperature, pressure, and atmospheric moisture alter the refractive properties of air. Consequently, knowledge of the temporal behaviour of atmospheric refractivity is important for understanding propagation conditions and for improving the planning and performance of radio communication systems.

A key parameter used to characterise the propagation environment is radio refractivity, which describes the influence of the atmosphere on the propagation of electromagnetic waves. It is primarily determined by atmospheric pressure, temperature, and water vapour pressure and is commonly expressed using the standard formulation recommended by the International Telecommunication Union (ITU-R, 2019). Variations in radio refractivity influence the degree of radio-wave bending and can contribute to changes in propagation range, signal strength, multipath effects, super-refraction, and atmospheric ducting. Since the refractivity field responds directly to changes in the thermodynamic state of the atmosphere, its temporal variability provides useful information about the atmospheric

conditions controlling radio-wave propagation.

Atmospheric moisture contributes significantly to radio refractivity, particularly in tropical environments. The refractivity of moist air consists of dry and wet components, with the dry component primarily determined by atmospheric pressure and temperature and the wet component strongly dependent on water vapour pressure. Although the dry component generally contributes the larger fraction of the mean surface refractivity, variations in atmospheric moisture can produce substantial changes in the total refractivity. This distinction between the contribution of a component to the mean refractivity and its contribution to temporal variability is important because a component that contributes less to the mean may nevertheless account for a substantial proportion of the observed fluctuations.

Lagos provides an important setting for investigating these relationships. As a tropical coastal environment, Lagos is influenced by maritime air masses, high atmospheric moisture, seasonal rainfall variability, and the seasonal migration of the Inter-Tropical Discontinuity. These processes produce substantial changes in temperature, atmospheric pressure, and moisture content and consequently affect the refractive state of the lower atmosphere. Studies across Nigeria and West Africa have reported pronounced seasonal variations in radio refractivity, generally with higher values during the wet season and lower values during the dry season, reflecting changes in atmospheric moisture (Adediji *et al.*, 2011; Falodun & Okeke, 2013; Akpotu, 2017., Emetere *et al.*, 2021; Sanyaolu & Sanyaolu, 2022; Ibanga *et al.*, 2024). Abimbola *et al.* (2021) similarly showed that near-surface radio refractivity across West Africa follows regional variations in atmospheric moisture associated with the seasonal cycle. More recent studies have further demonstrated the importance of temperature and moisture in controlling the spatial and temporal distribution of

refractivity across West Africa, including the influence of the Inter-Tropical Discontinuity on refractivity-gradient variability (Emmanuel *et al.*, 2024).

Despite these advances, much of the existing work on radio refractivity over Nigeria has concentrated on seasonal, diurnal, spatial, or propagation-related characteristics. Comparatively less attention has been given to the long-term temporal behaviour of refractivity at individual coastal locations and, particularly, to separating the contribution of the dry and wet components to the mean state from their contributions to temporal variability. This distinction is important because the magnitude of mean refractivity alone does not necessarily indicate which atmospheric component is responsible for its fluctuations. A long-term monthly analysis can therefore provide a more comprehensive understanding of the atmospheric processes underlying refractivity variability in a tropical coastal environment.

The present study investigates the temporal variability of surface radio refractivity over Lagos, Nigeria, using monthly meteorological observations covering the 30-year period from 1995 to 2024. Radio refractivity and its dry and wet components are derived from temperature, atmospheric pressure, and vapour pressure observations. Descriptive statistics and component-based variance decomposition are used to quantify the relative contributions of the dry and wet terms to the mean and temporal variability of refractivity. The temperature–pressure relationship is further examined using cross-correlation analysis, while linear, quadratic, and cubic regression models are applied to characterise the long-term trend of the refractivity series.

The contribution of this study lies in providing a long-term assessment of radio refractivity over Lagos that distinguishes between the factors controlling its mean magnitude and those controlling its temporal variability. In particular, the study demonstrates that the component



contributing most to the climatological mean is not necessarily the component responsible for most of the temporal fluctuations. By explicitly quantifying these contributions over a continuous 30-year record, the study provides additional insight into the meteorological controls of radio refractivity in a humid tropical coastal environment and contributes to the understanding of atmospheric variability relevant to radio-wave propagation over Lagos.

2.0 Data and Method of Analysis

2.1 Data and Sources

The meteorological data used in this study comprise monthly temperature (T), atmospheric pressure (P), and water vapour pressure (e) for the period 1995-2024, sourced from Nigerian Meteorological Agency (NiMet). The temperature data comprised monthly maximum and minimum values, which were pre-processed to obtain monthly and annual mean time series as

$$T = \frac{T_{\max} + T_{\min}}{2}$$

and converted from degree celsius (T_C) to kelvin (T_K) as $T_C + 273.15$

The NiMet atmospheric pressure values expressed in mb and are equivalent to hPa, while vapour pressure given in was appropriately in hPa

2.2 Method of Analysis

The NiMet monthly temperature, atmospheric pressure and vapour-pressure data were arranged as continuous monthly time series vectors covering January 1995 to December 2024 (360 months).

Surface radio refractivity N was calculated from temperature, atmospheric pressure and vapour pressure data using the standard Smith-Weintraub formulation:

$$N = 77.6 \left(\frac{P}{T_K} \right) + 3.73 \times 10^5 \left(\frac{e}{T_K^2} \right) \quad (1)$$

where N = radio refractivity (N-units); P = atmospheric pressure (hPa); T_K = absolute air temperature (K) and e = water-vapour pressure.

The first term represents the dry component of refractivity, while the second represents

the wet component, which is particularly sensitive to atmospheric moisture. This formulation is consistent with ITU-R (ITU-R, 2019).

The quantification of the relative contributions of the dry and the wet terms to the mean and temporal variability of refractivity over the over January 1995-December 2024 months were performed as:

A. Percentage contribution to mean refractivity

$$\bar{N}_d = \frac{1}{360} \sum_{i=1}^{360} N_{d,i} \text{ and } \bar{N}_w = \frac{1}{360} \sum_{i=1}^{360} N_{w,i} \quad (2)$$

where $N = \bar{N}_d + \bar{N}_w$ and $\bar{N}_d$, $\bar{N}_w$ are the mean dry and wet terms respectively. The percentage contributions C_d and C_w were then calculated as

$$C_d = 100 \frac{\bar{N}_d}{N} \text{ and } C_w = 100 \frac{\bar{N}_w}{N} \quad (3)$$

B. Contribution to temporal variability

The variance of N over the period under study was computes as

$$\text{Var}(N) = \text{Var}(N_d) + \text{Var}(N_w) + 2\text{cov}(N_d, N_w) \quad (4)$$

The third term arises from the fact that, the variability of total refractivity depends not only on the individual variances of the dry and wet terms, but also on whether they vary together or in opposite directions. The percentage variance of the terms was computed as

$$V_d = 100 \frac{\text{Var}(N_d)}{\text{Var}(N)} \text{ and } V_w = 100 \frac{\text{Var}(N_w)}{\text{Var}(N)} \text{ and } V_c = 100 \frac{2\text{cov}\text{Var}(N_w)}{\text{Var}(N)} \quad (5)$$

V_d , V_w and V_c are variance contributions dry, wet covariance respectively.

Time series plots, descriptive and diagnostic statistics were performed to characterise the overall variability of the meteorological parameters and computed refractivity within the study time frame. Linear associations among the meteorological variables and radio refractivity were examined using Pearson correlation coefficients. Monthly climatological means were determined for



meteorological parameters to separate seasonal variability from longer-term and interannual variations. Trend and stationarity analyses were then performed to determine temporal trends and stationarity. Polynomial regression model was further applied to assess whether or not the refractivity exhibited significant long-term changes or non-stationary behaviour.

3.0 Results and Discussion

Radio refractivity time series over Lagos (1995-2024) is shown in Fig. 1. The minimum value of 317.97 N-units and the

maximum value of 389.20 N-units occurred in January 2008 and March 2008 respectively. The mean value over the 360 months of observation is 376.79 N-units, with a standard deviation of 7.48 N-units. The January 2008 minimum was the deepest (317.97 N-units) throughout the observation period. There was the need to determine the specific meteorological condition that accounts for this prominent deep. So, the time series of each meteorological variable was examined.

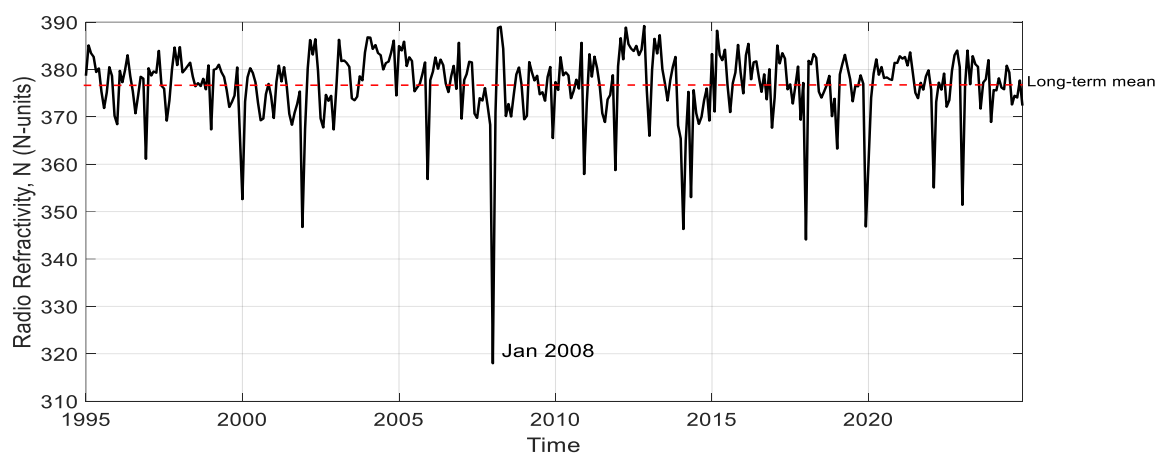


Fig. 1: Refractivity Time Series over Lagos (1995-2024)

Fig 2(a-d) displays the time series of the meteorological variables used to calculate the refractivity. Monthly mean atmospheric temperature and pressure varied approximately antiphase (Fig. 2a & b), while monthly radio refractivity and water vapour pressure varied synchronously (Fig. 2c & d). It is clear that the deep of refractivity in January 2008 was possibly due corresponding the deep in water vapour (15 hPa)).

This synchronous variation appears to be physically consistent with the phenomenon of high sensitivity of refractivity to changes in atmospheric moisture, arising basically from the relatively large coefficient multiplying the wet term in eqn. 1. It also appears to be physically plausible in the context of the location of Lagos as a coastal city. Moisture laden maritime air mass from

the Atlantic Ocean, along with seasonal changes in atmospheric circulation, rainfall and the north-south migration of the Intertropical Discontinuity (ITD), can influence surface water-vapour content and, consequently, radio refractivity. Some recent publications have reported that atmospheric moisture controls the variation of refractivity over West Africa (e.g. Abimbola *et al.*, 2021). However, Bello *et al* (2024) demonstrated that the wet term of the refractivity model accounted for approximately 30-32% of the observation of the phenomenon in Warri and Ogoja, while the dry term contributed the larger portion, especially in the coastal region. To further investigate this, the mean contributions of the dry and wet components to surface radio refractivity were quantified by decomposing the refractivity equation into its hydrostatic



and moisture-dependent terms, as well as temporal variability of refractivity. The results are shown in Tables 1 and 2.

The temporal variance decomposition further indicated that the dry and wet terms accounted for 5.43% and 109.42% of the

total refractivity variance, respectively, with a covariance contribution of -14.85%. These results distinguish the contribution of each component to the climatological mean refractivity from its contribution to temporal variability over Lagos during 1995–2024.

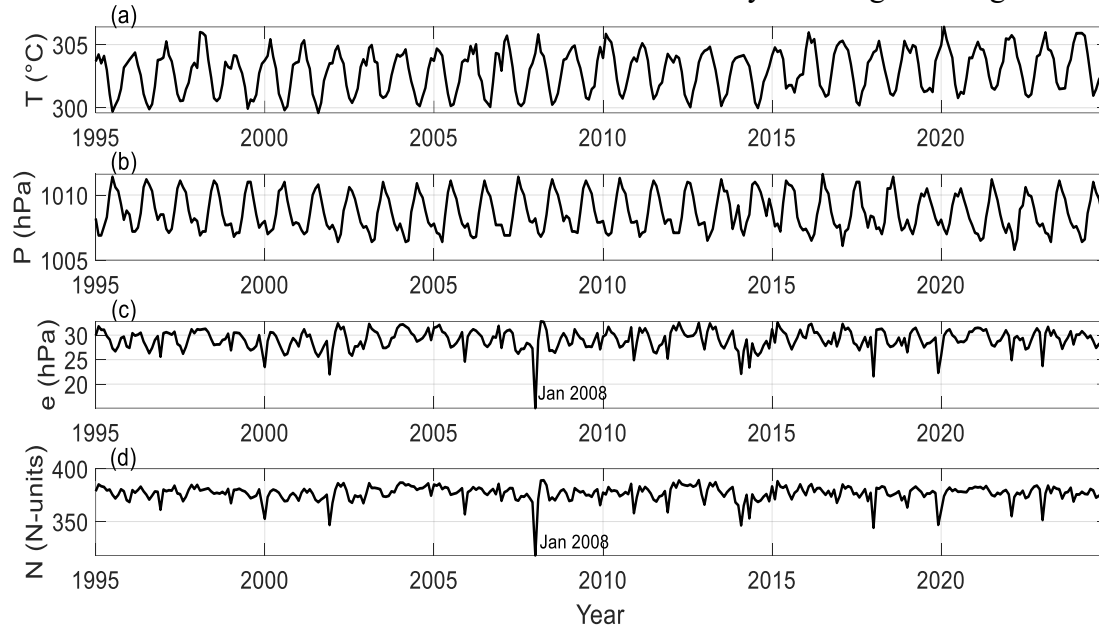


Fig. 2: Monthly Meteorological Variables and Radio Refractivity over Lagos, 1995–2024

Table 1: Percentage Contribution to Mean Refractivity

Component	Mean (N-units)	SD	Minimum	Maximum	Contribution (%)
Dry refractivity	258.3790	1.7422	255.1404	261.8773	68.59
Wet refractivity	118.3158	7.8224	60.8217	132.0315	31.41
Total	376.6948	7.4780	317.9175	389.0971	100.00

It could evident that the dry component accounted for ~68.60% of the mean total

refractivity, while, in contrast, the wet component contributed 31.41%.

Table 2: Percentage Contribution to Variability of Refractivity

Component	Variance/Covariance	Contribution to Total Variance (%)
Dry refractivity	3.035293	+5.43
Wet refractivity	61.190612	109.42
Dry-wet refractivity	-4.152864	-14.85
Total Refractivity	55.920177	100.00
Dry variance decomposition	—	100.00



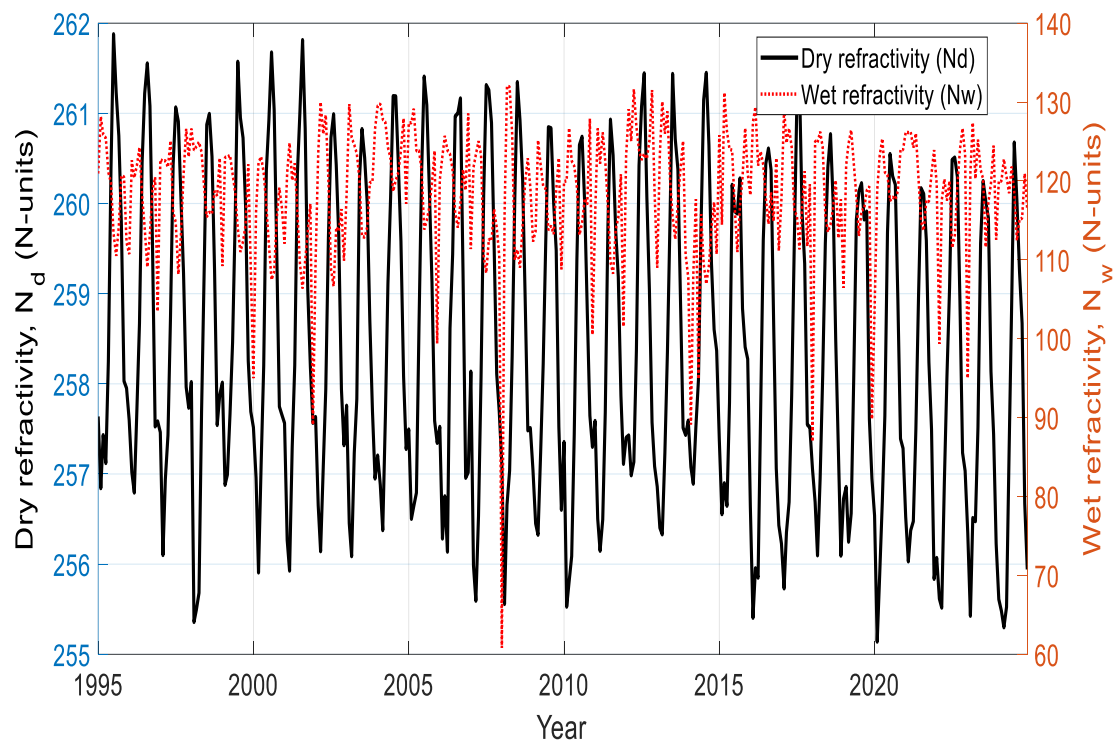


Fig. 3: Monthly Dry and Wet Refractivity Components over Lagos (1995-2024)

The monthly contribution of the mean dry and wet terms are displayed in Fig 3 which tends to provide evidence that dry term predominates. The results of these analyses are broadly consistent with previous works e.g., Abimbola *et al.* (2021), especially with regard to the dominance of atmospheric moisture as the principal driver of temporal variations in surface radio refractivity over West Africa. They also agree with Bello *et al.* (2024), who found that the wet term contributed approximately 30–32% to the mean refractivity in Warri and Ogoja, with the dry term accounting for the larger share. However, this study extends these findings by separating the contribution to the climatological mean from that of the temporal variance. It shows explicitly that although the dry term dominates the magnitude of mean refractivity, variations in atmospheric moisture dominates its temporal variability over Lagos during 1995-2024.

To quantify the antiphase variation of atmospheric mean temperature with pressure, cross-correlation between the variables was performed. The result revealed a strong inverse zero-lag correlation ($r_{P,T}(0) = -0.8937$), suggest that the two variables exhibit contrasting temporal behaviour with regard to the dry-air component of the refractivity. The cross-correlation function also exhibits an oscillatory pattern (Fig. 4), indicating recurrent periodic structure in the temperature-pressure relationship. This strong contemporaneous inverse association suggests that periods of relatively higher temperature generally coincide with lower atmospheric pressure and vice versa. On the other hand, the oscillatory behaviour is consistent with the strong seasonal cycle characteristic of the Lagos atmosphere.

For small changes, the relative variation of this component can be approximated by

$$\frac{\delta N_d}{N_d} \approx \frac{\delta P}{P} - \frac{\delta T}{T}$$



where δN_d , δP and δT are the small changes in dry component of the refractivity, atmospheric pressure and temperature respectively.

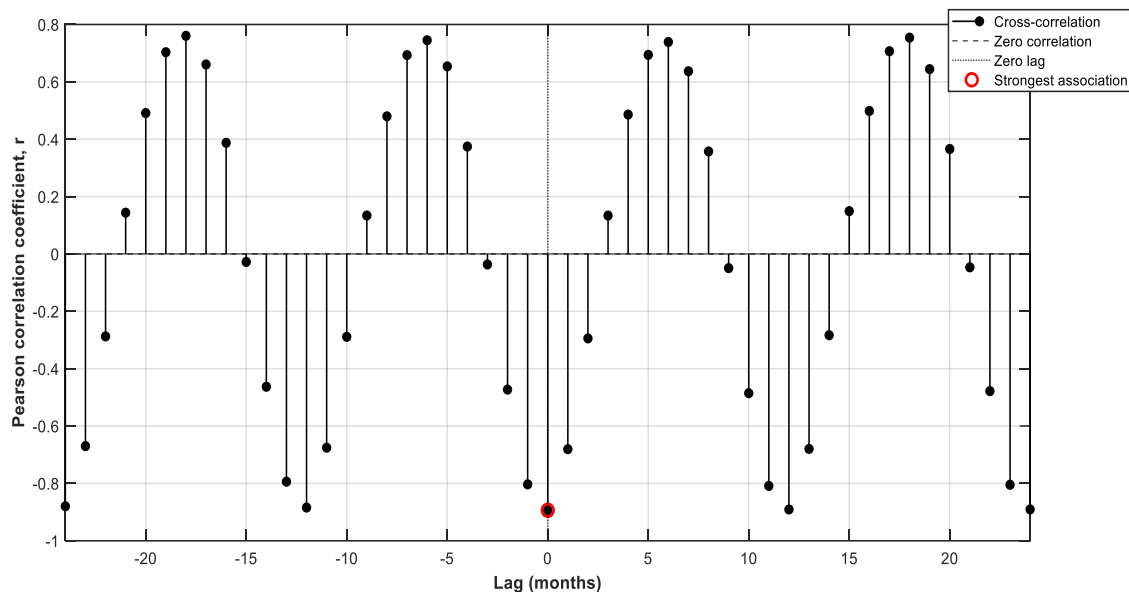


Fig. 4: Cross-correlation of atmospheric temperature and pressure

An increase in pressure accompanied by decrease in temperature tends to enhance dry-air component of refractivity and vice versa. However, the overall response of refractivity also depends on vapour pressure, which can be a substantial contributor in the humid maritime environment of Lagos. Therefore, the observed synchronisation between refractivity and water vapour pressure in this study highlights the potential importance of moisture variability in modulating the near-surface refractive environment over Lagos.

The cross-correlation function also exhibits an oscillatory pattern, indicating recurrent periodic structure in the temperature-pressure relationship. The strong contemporaneous inverse association suggests that periods of relatively higher temperature coincide with lower atmospheric pressure and vice versa, while the oscillatory behaviour is consistent with the strong seasonal cycle characteristic of the Lagos atmosphere. Some recent results on Lagos refractivity e.g. Adeniji *et al.* (2021) are consistent with the seasonal variability of

refractivity in the humid, coastal environment. The zero-lag correlation $r_{P,T}(0) = -0.8937$ reported in this study goes further to demonstrate a very strong contemporaneous relationship between monthly temperature and pressure, the oscillatory cross-correlation structure reveals the recurring seasonal character of this coupling. Combined with our variance decomposition, the results suggest that temperature and pressure form a strongly coupled dry-atmospheric background, whereas moisture variations superimpose the larger temporal fluctuations in total refractivity.

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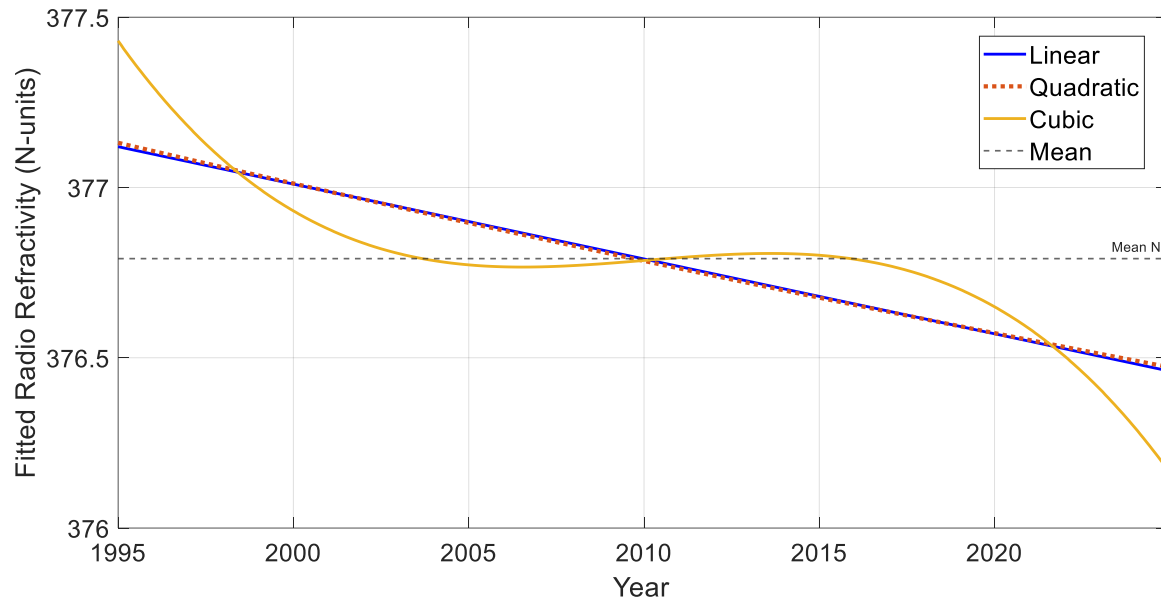


Fig. 5: Polynomial Trend Components of Radio Refractivity

4.0 Conclusion

In this study, monthly temperature, atmospheric pressure and vapour pressure data for Lagos from 1995-2024 were used to compute radio refractivity and its dry and wet components. Descriptive statistics, component contribution and variance decomposition, temperature-pressure correlation, and linear, quadratic and cubic polynomial regression were employed to examine the temporal characteristics of refractivity. The results gave a mean radio refractivity N-units, with a standard deviation of 7.48 N-units and a range of 317.97-389.20 N-units. The dry component contributed 68.6% to the mean refractivity, while the wet component contributed 31.4%. However, the wet component accounted for 109.42% of the total temporal variance, compared to 5.43 for the dry component, while the covariance contribution was -14.85%. This showed that atmospheric moisture variations constitute the dominant source of temporal variability in radio refractivity over Lagos.

The temperature and pressure series exhibited a strong inverse zero-lag relationship, with a correlation coefficient of approximately -0.894, reflecting their pronounced seasonal variability. Polynomial regression revealed a very weak long-term decline in refractivity, with a linear slope of $-0.022 \text{ units yr}^{-1}$ and $R^2 = 0.000649$. The quadratic model produced virtually identical results, while the cubic model increased R^2 only marginally to 0.000886. Overall, the findings indicate that radio refractivity over Lagos during 1995-2024 was characterised by substantial temporal variability, principally associated with atmospheric moisture, rather than by significant persistent linear or low-order non-linear trend.

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Declaration

Conflict of Interest

The authors declare that there is no known conflict of interest or personal relationships that have influence the work reported in this paper.

Ethical Consideration

Not applicable

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Author Contributions

All components of the work were carried out by the author.



