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Radio Refractivity and Gradient Variations Across West Africa Climatic Zones: Implications for Microwave Systems

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Abstract

This study investigates the spatial and temporal variations of radio refractivity and refractivity gradient across different climatic zones in West Africa using 22 years of reanalysis meteorological data (temperature, pressure, and relative humidity). Ten representative locations from coastal, rainforest, savannah, and desert regions were analyzed to characterize radio wave propagation mechanisms across the sub-region. Surface refractivity exhibited distinct patterns, with values ranging from 372 to 419 N-units, showing clear seasonal and climatic zone dependencies. The refractivity gradient analysis revealed that tropospheric ducting is the predominant propagation condition across most locations, except for Monrovia where sub-refraction exceeds ducting at 1000 hPa and 975 hPa pressure levels. Atmospheric ducting was particularly pronounced in savanna and desert regions due to dry air conditions and temperature inversions. Super-refractive conditions prevailed at 975 hPa and 950 hPa in all climatic zones, especially during the dry season. This comprehensive characterization of radio refractivity parameters provides essential information for optimizing microwave communication systems design and performance across West Africa's diverse climatic regions.

Keywords: Radio refractivity; refractivity gradient; tropospheric ducting; super-refraction; climatic zones; West Africa; microwave communications.

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1. Introduction

Radio refractivity is the bending of radio signal as it propagates through media, the propagation characteristics of radio waves are heavily influenced by atmospheric conditions such as scattering, absorption, reflection, and refraction within the Earth's troposphere govern radio wave behaviour. Radio refractivity plays a critical role in determining signal paths within this region. Radio links are subject to variations in atmospheric parameters like pressure, temperature, and relative humidity, which affect the frequency and power of radio signals [1]. Temperature and pressure have an inverse relationship with signal strength, while relative humidity can have both positive and negative effects depending on the frequency and conditions [2]. Vertical refractivity gradient is the difference in the refractivity values at difference height. 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. The profile of the atmospheric refractivity gradient at a height of 1 km above the ground surface is important when studying trapping, super-refraction, and sub-refraction and ducting phenomenon because it determines the degree of curvature of radio signal propagating in the atmosphere [3]. However, anomalous propagation conditions in the atmosphere is as a result of changes in atmospheric refractivity with height [4]. Refractivity gradients of – 40 N/Km are considered normal refraction, while values between -41 and -156 N/km indicates super refraction, which can lead to extended radio range. Refractivity gradients of – 157 N/Km or less indicating ducting, where signals can be trapped and travel long distances [5]. Several researchers have done a lot of work on refractivity and refractivity gradient. [6] studied the radio refractivity over the first 100 Km in Akure. The result obtained showed that worst propagation are observed at 1500 – 1800 and 1700 – 1900 local time during the dry and wet seasons. ; [5] studied the Vertical profile of radio refractivity gradient in Akure, South-West, Nigeria and reported that propagation conditions varied throughout the year, they observed that sub – refraction was more prevalent from January to July while super refraction and ducting occurred primarily between August and December.; [7] reported the average values of refractivity of -52.8 N- units per km and high values of refractivity during wet seasons using two years data over Akure. [8] studied the diurnal and seasonal variation of surface refractivity over Nigeria; revealed that the value of surface refractivity increases from arid region in the north to the coastal area of the country. [9] reported on estimation of radio refractivity from a decade satellite derived metrological data for west Africa that refractivity found to range between -46. 46 and – 29. 51 N –units/ km across West Africa splitting the region between sub – refraction and super refraction. Several researches on radio refractivity and refractivity gradient have been carried out but this study aims to characterize radio refractivity and its vertical gradient across the three critical pressure level in four distinct climatic zones in West Africa using 22 years of reanalysis meteorological data where all of the researchers mentioned above have not covered. This research will analysis temporal and spatial variations in refractivity parameters that will provide valuable insights for optimizing communication system design and performance throughout the region.

2. Methodology

2.1 Study Area and Data Collection

This study analyzed 22 years (2000-2021) of reanalysis meteorological data (temperature, relative humidity, and pressure) for ten locations representing four major climatic zones in West Africa (Figure 2) ERA5 data was collected through the Copernicus Climate Data Store using its Application Programming Interface (API) Ref [12]. The CDS API allows users to programmatically access and retrieve data from the CDS platform:

- **Coastal Zone**: Dakar (Senegal), Accra (Ghana), Monrovia (Liberia), Freetown (Sierra Leone)
- **Rainforest Zone**: Douala (Cameroon), Abidjan (Côte d'Ivoire)
- **Savanna Zone**: Kano (Nigeria), Mopti (Mali)
- **Desert Zone**: Niamey (Niger), Ouagadougou (Burkina Faso)

Table 1: Geographic Coordinates and Climatic Classification of Study Locations

Location	**Country**	**Latitude (°N)**	**Longitude (°E)**	**Climatic Zone**	**Average Annual Rainfall (mm)**
Dakar	Senegal	14.69	-17.45	Coastal	514.00
Accra	Ghana	5.60	-0.17	Coastal	810.00
Monrovia	Liberia	6.31	-10.80	Coastal	4624.00
Freetown	Sierra Leone	8.48	-13.23	Coastal	3657.00
Douala	Cameroon	4.05	9.77	Rainforest	3891.00
Abidjan	Côte d'Ivoire	5.36	-4.00	Rainforest	1761.00
Kano	Nigeria	12.00	8.52	Savanna	873.00
Mopti	Mali	14.52	-4.09	Savanna	497.00
Niamey	Niger	13.51	2.11	Desert	483.00
Ouagadougou	Burkina Faso	12.37	-1.52	Desert	788.00

The reanalysis data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset, which provides hourly estimates of atmospheric variables at multiple pressure levels with a spatial resolution of 0.25° × 0.25°. Data were extracted at three pressure levels: 1000 hPa (approximately 110.88 m), 975 hPa (approximately 323.38 m), and 950 hPa (approximately 540.33 m) to analyse refractivity variations with altitude in the 10 locations as shown in Table 1 and Figure 1.

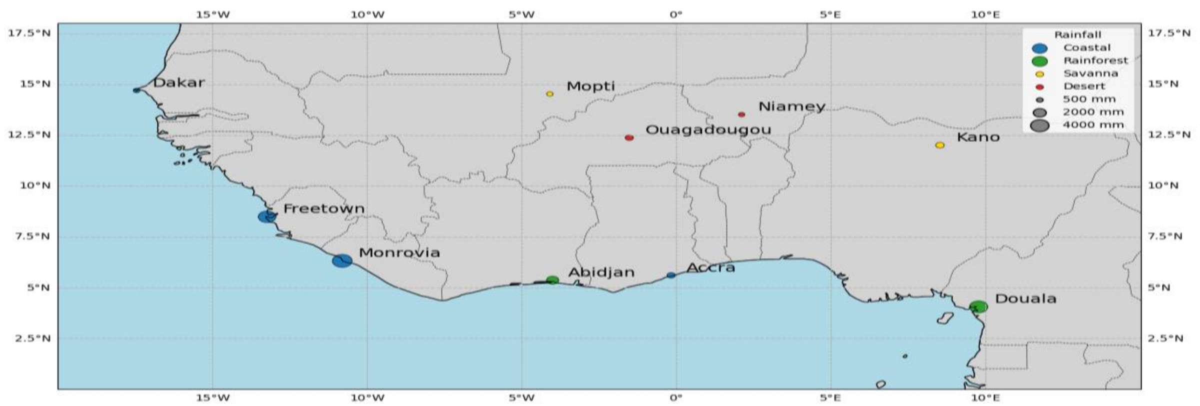


Figure 1: Selected locations representing four major **West Africa** Climatic Zones and Average Annual Rainfall (mm)

2.2 Calculation of Radio Refractivity

Surface refractivity (N) was calculated using the formula recommended by the International Telecommunication Union (11): $N = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \ (N - units)\}$ (1)

Where: P is the atmospheric pressure (hPa)

T is the absolute temperature (K)

e is the water vapor pressure (hPa)

The water vapour pressure (e) was calculated using: $e = \frac{H}{100} \times 6.1121 exp(\frac{17.592t}{t+240.97})$ (2)

Where: H is the relative humidity (%)

t is the air temperature (°C)

2.3 Calculation of Refractivity Gradient

The refractivity gradient (dN/dh) between two pressure levels was calculated using:

$$\frac{dN}{dh} = \frac{N2 - N_1}{h_2 - h_1} \ (N - units/km) \quad (3)$$

where: N_1 *and* N_2 are the refractivity values at heights h_1 *and* h_2 respectively

$h_2 - h_1$ is the height difference in kilometres

2.4 Data Analysis

The calculated refractivity and refractivity gradient values were analysed to:

1. Determine temporal variations of surface refractivity across the study period (2000-2021)
2. Characterize refractivity gradient distributions at different pressure levels
3. Identify predominant propagation conditions (sub-refraction, super-refraction, ducting) across different climatic zones
4. Assess seasonal and diurnal variations of refractivity gradient in each climatic zone

Statistical analyses were performed to determine means, standard deviations, and percentages of occurrence for different propagation conditions. Time series analysis was conducted to identify long-term trends and seasonal patterns in refractivity parameters.

3. Results and Discussion

3.1 Temporal Variations of Surface Refractivity

3.1.1 Rainforest Climatic Zone

Figure 2a and 2b illustrate the surface refractivity time series for Abidjan and Douala (rainforest climatic zone) over the 22-year study period. Both locations exhibited similar periodic fluctuation patterns, with values ranging from 372 to 419 N-units. In Abidjan, peak refractivity values of 419 N-units were observed in 2005, 2010, 2019, and 2020, while the lowest value of 372 N-units occurred in 2015. These variations are primarily attributed to changes in atmospheric humidity, with higher refractivity corresponding to periods of increased rainfall and humidity, and lower refractivity during drier periods. The consistent pattern observed in Douala reflects the relatively stable tropical rainforest climate characterized by high humidity throughout the year.

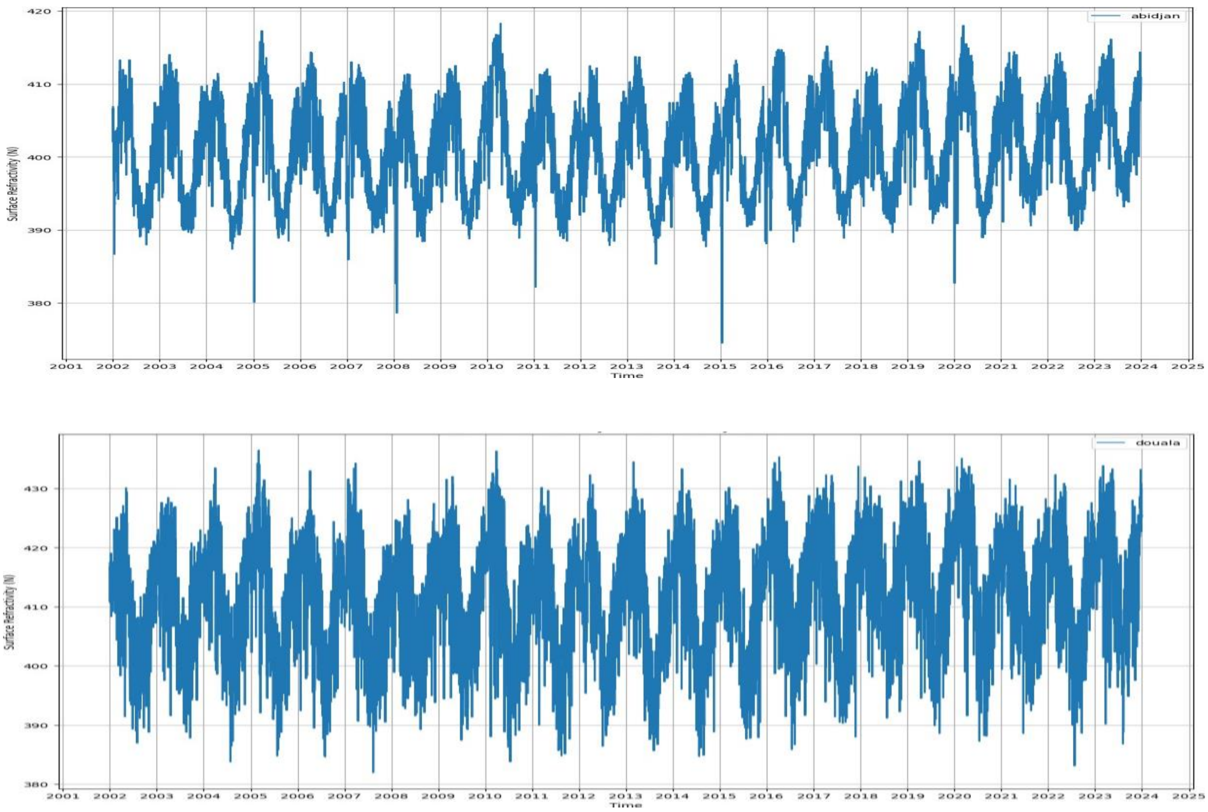


Figure 2a & 2b: Time series of surface refractivity (N, in N-units) in rainforest zones: (a) Abidjan and (b) Douala, from 2000 to 2021, highlighting periodic fluctuations

3.1.2 Savanna Climatic Zone

Surface refractivity time series for Kano and Mopti (savanna climatic zone) are presented in Figure 3a and 3b. These locations showed similar fluctuation patterns to those observed in the rainforest zone, but with generally lower refractivity values, reflecting the lower average humidity levels in savanna regions. The synchronization of peak values (in 2005, 2010, 2019, and 2020) across different climatic zones suggests the influence of larger regional or global climate drivers on refractivity patterns across West Africa.

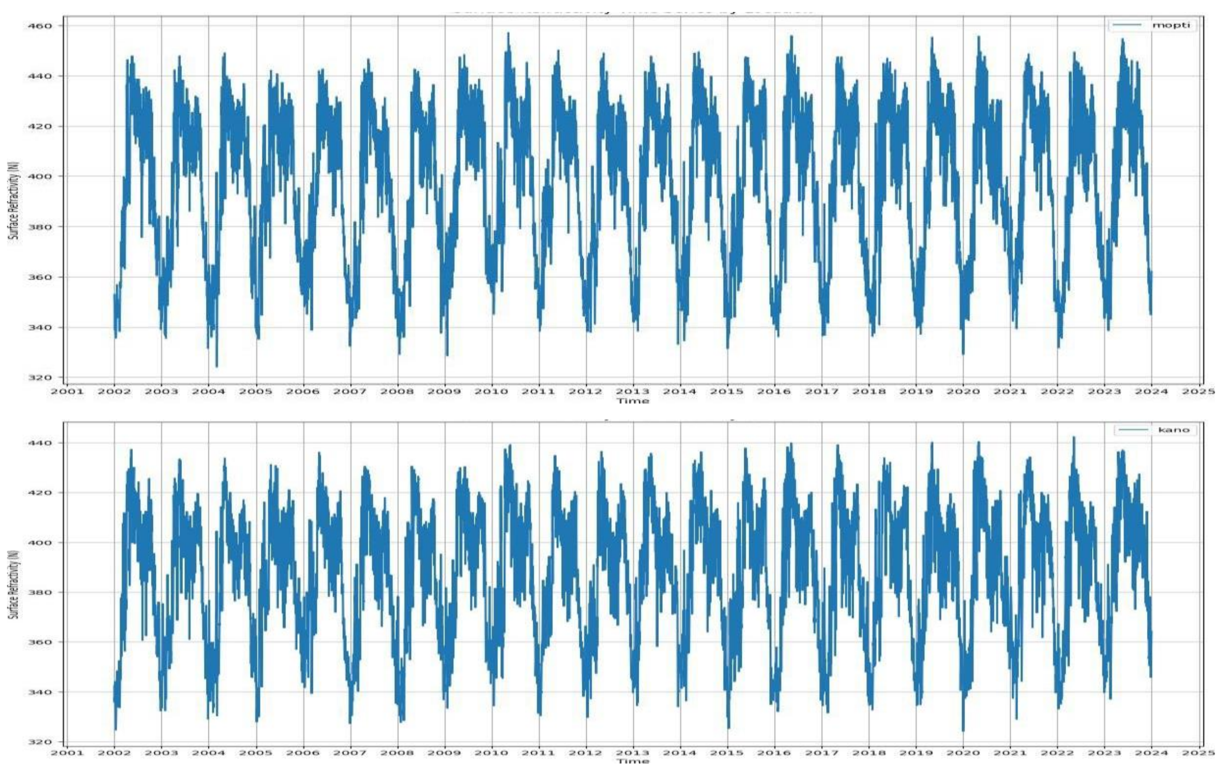
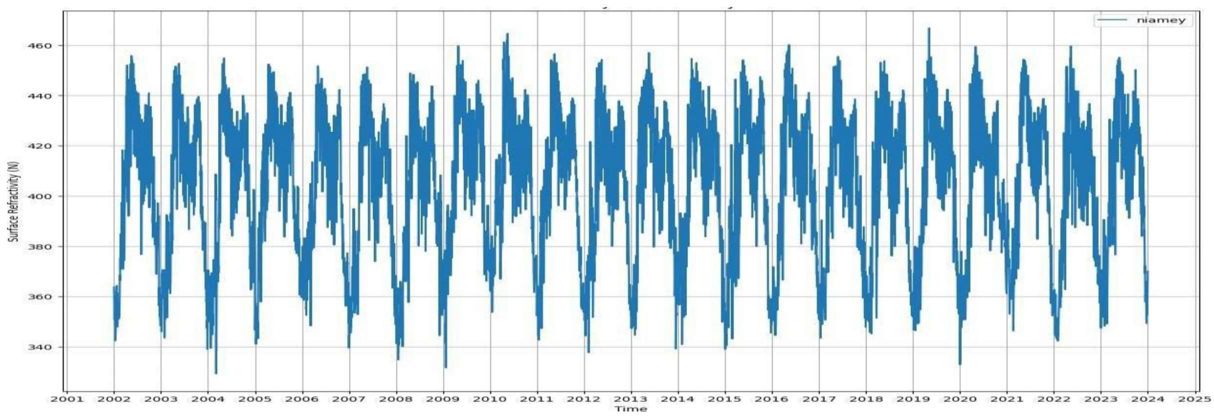


Figure 3a & 3b: Surface refractivity time series in savanna zones: (a) Kano and (b) Mopti, showing peak values in 2005 and 2010

3.1.3 Desert Climatic Zone

Figure 4a and 4b display surface refractivity variations in Niamey and Ouagadougou (desert climatic zone). Niamey exhibited a refractivity pattern similar to that of other zones, while Ouagadougou showed its minimum refractivity values (approximately 372 N-units) in both 2015 and 2020. Desert locations generally demonstrated lower average refractivity values and greater variability than coastal and rainforest zones, consistent with their characteristically low humidity and substantial temperature fluctuations.



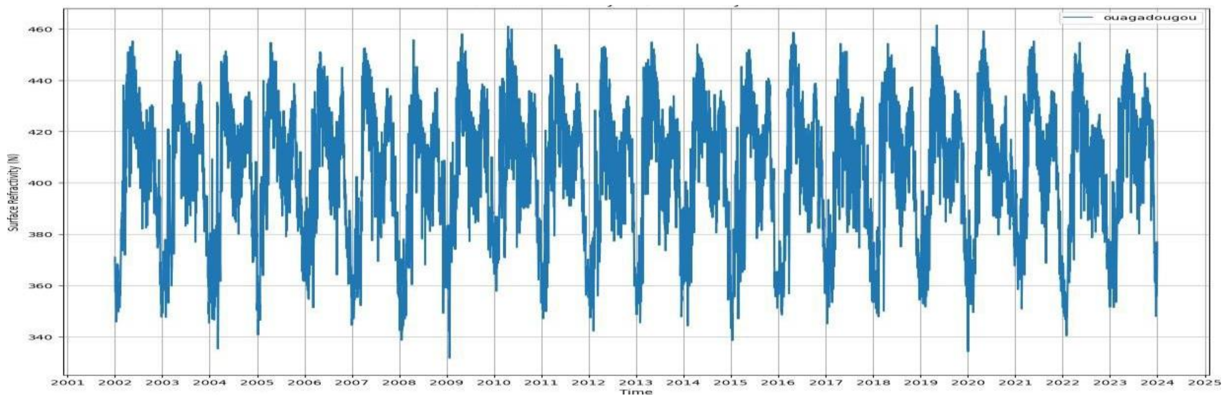


Figure 4a & 4b: Surface refractivity time series in desert zones: (a) Niamey and (b) Ouagadougou, with minima in 2015

3.1.4 Coastal Climatic Zone

The surface refractivity time series for Freetown and Dakar (coastal climatic zone) are shown in Figure 5a and 5b. These locations exhibited periodic fluctuations with patterns similar to those observed in other climatic zones. Coastal locations typically maintained higher refractivity values than inland areas, reflecting the consistent influence of maritime air masses with higher humidity levels.

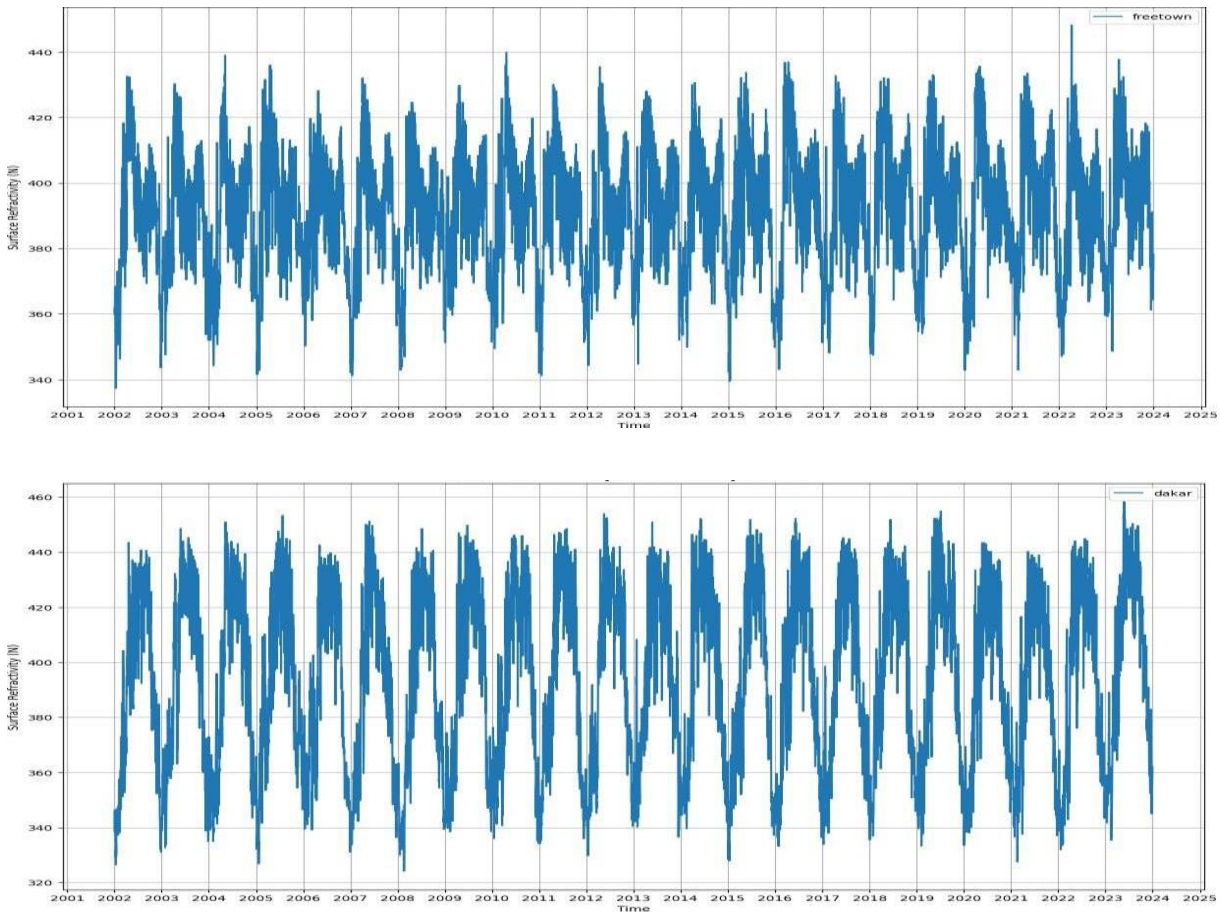


Figure 5a & 5b: Surface refractivity time series in coastal zones: (a) Freetown and (b) Dakar, reflecting stable maritime influence

Table 2: Statistical Summary of Surface Refractivity (N-units) Across Climatic Zones (2000-2021)

Climatic Zone	Location	Min.	Max.	Mean	Standard Deviation	CV (%)
Coastal	Dakar	346	412	378.6	12.4	3.3
	Accra	357	418	390.2	10.5	2.7
	Monrovia	368	424	401.7	9.8	2.4
	Freetown	361	420	395.3	10.2	2.6
Rainforest	Douala	370	419	403.8	8.6	2.1
	Abidjan	372	419	402.5	9.1	2.3
Savanna	Kano	332	402	365.7	15.8	4.3
	Mopti	320	395	357.2	17.3	4.8
Desert	Niamey	315	392	349.6	18.9	5.4
	Ouagadougou	318	397	352.1	18.2	5.2

3.2 Refractivity Gradient Variations with Altitude

Figures 6 through 9 illustrate the refractivity gradient variations with altitude for the four climatic zones. Across all zones, a consistent pattern was observed: refractivity gradient decreased (became more negative) with increasing height above ground level. This pattern was evident at all three pressure levels: 1000 hPa (110.88 m), 975 hPa (323.38 m), and 950 hPa (540.33 m).

The decrease in refractivity gradient with altitude can be attributed to the vertical changes in temperature and pressure in the lower troposphere. As altitude increases, both temperature and pressure typically decrease, affecting the refractivity profile (Quantify gradients in appendix II). The steepest refractivity gradients were generally observed nearest to the Earth's surface (1000 hPa level), particularly in coastal and rainforest zones where significant humidity variations occur.

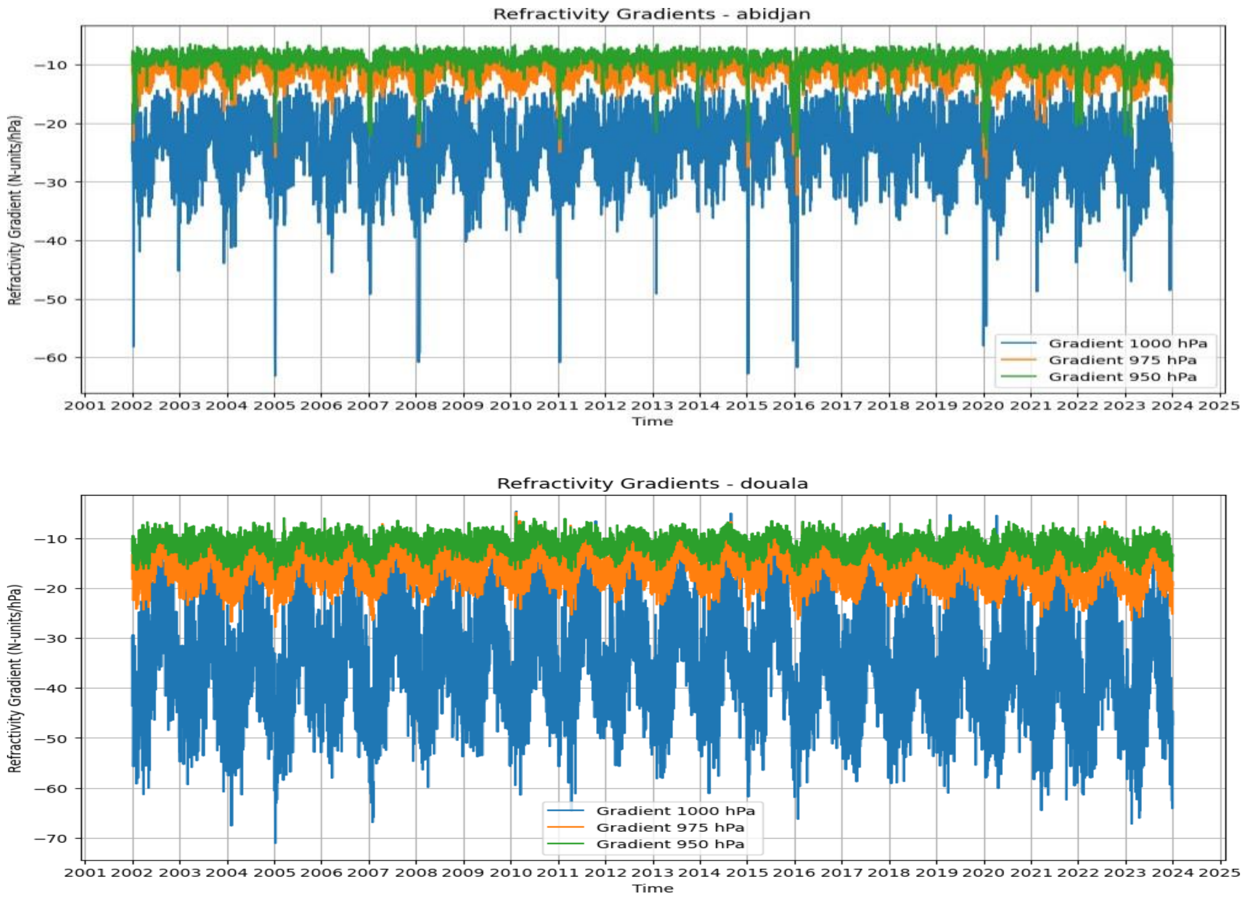


Figure 6a & 6b: Refractivity gradient (dN/dh, in N/km) profiles in rainforest zones: (a) Abidjan and (b) Douala, at 1000 hPa, 975 hPa, and 950 hPa

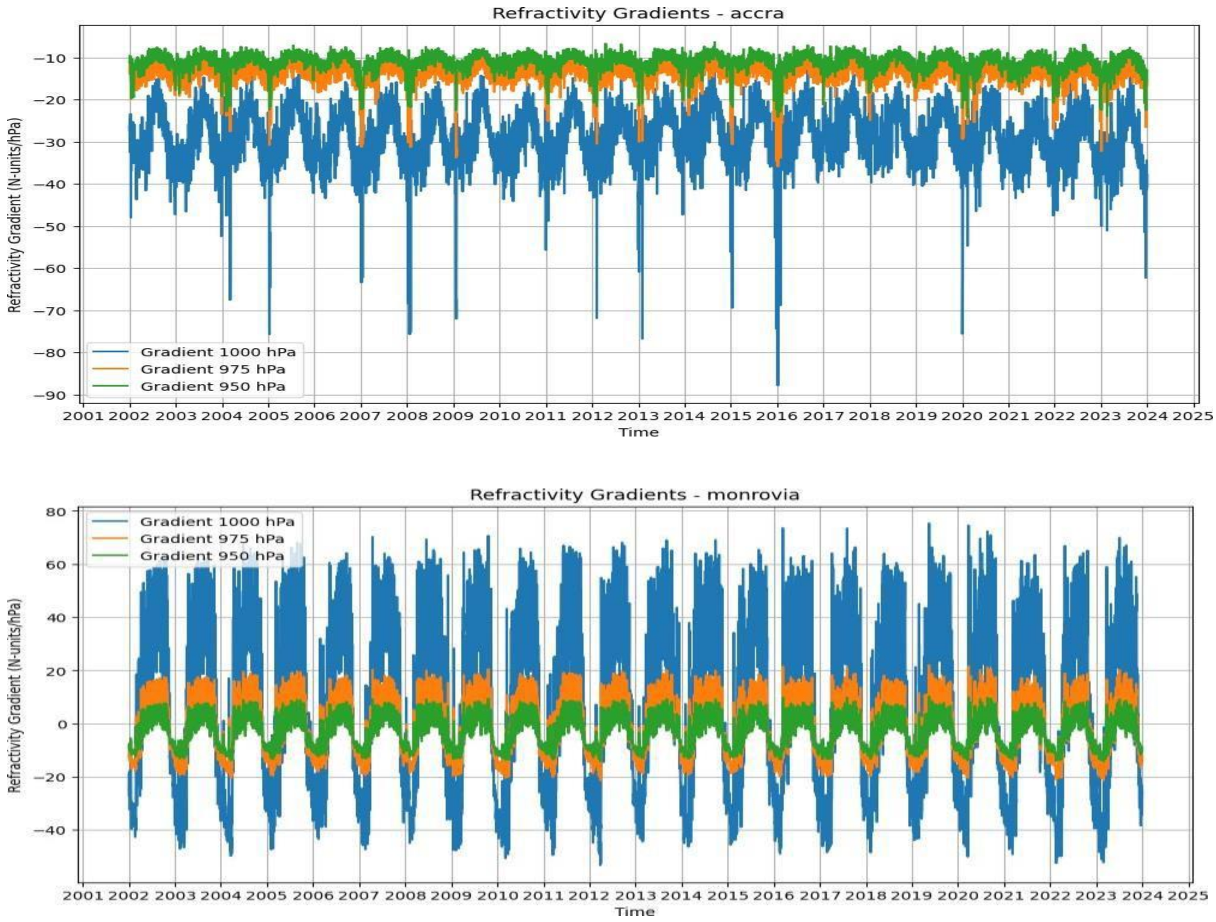
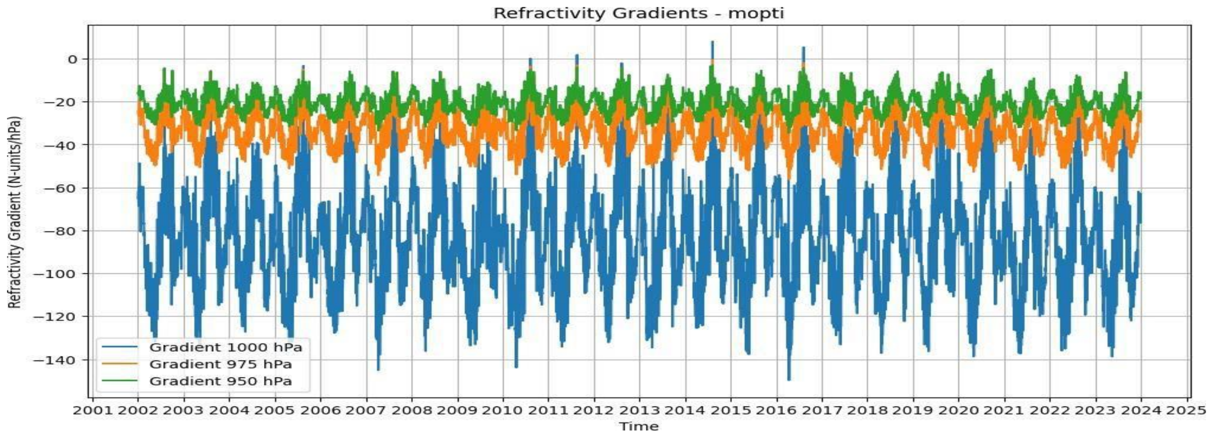


Figure 7a & 7b: Refractivity gradient profiles in coastal zones: (a) Accra and (b) Monrovia, showing altitude-dependent trends



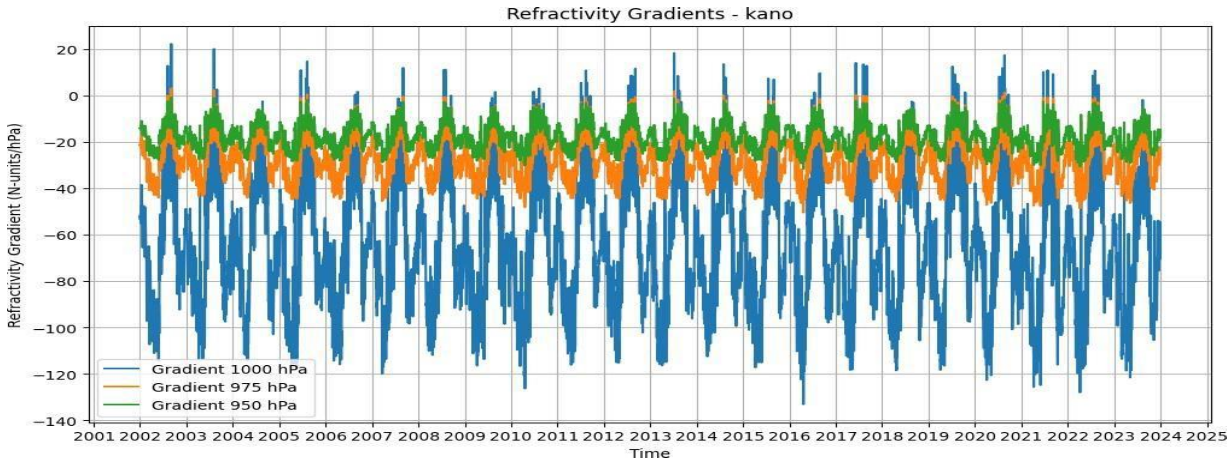


Figure 8a & 8b: Refractivity gradient profiles in savanna zones: (a) Kano and (b) Mopti, indicating ducting near the surface

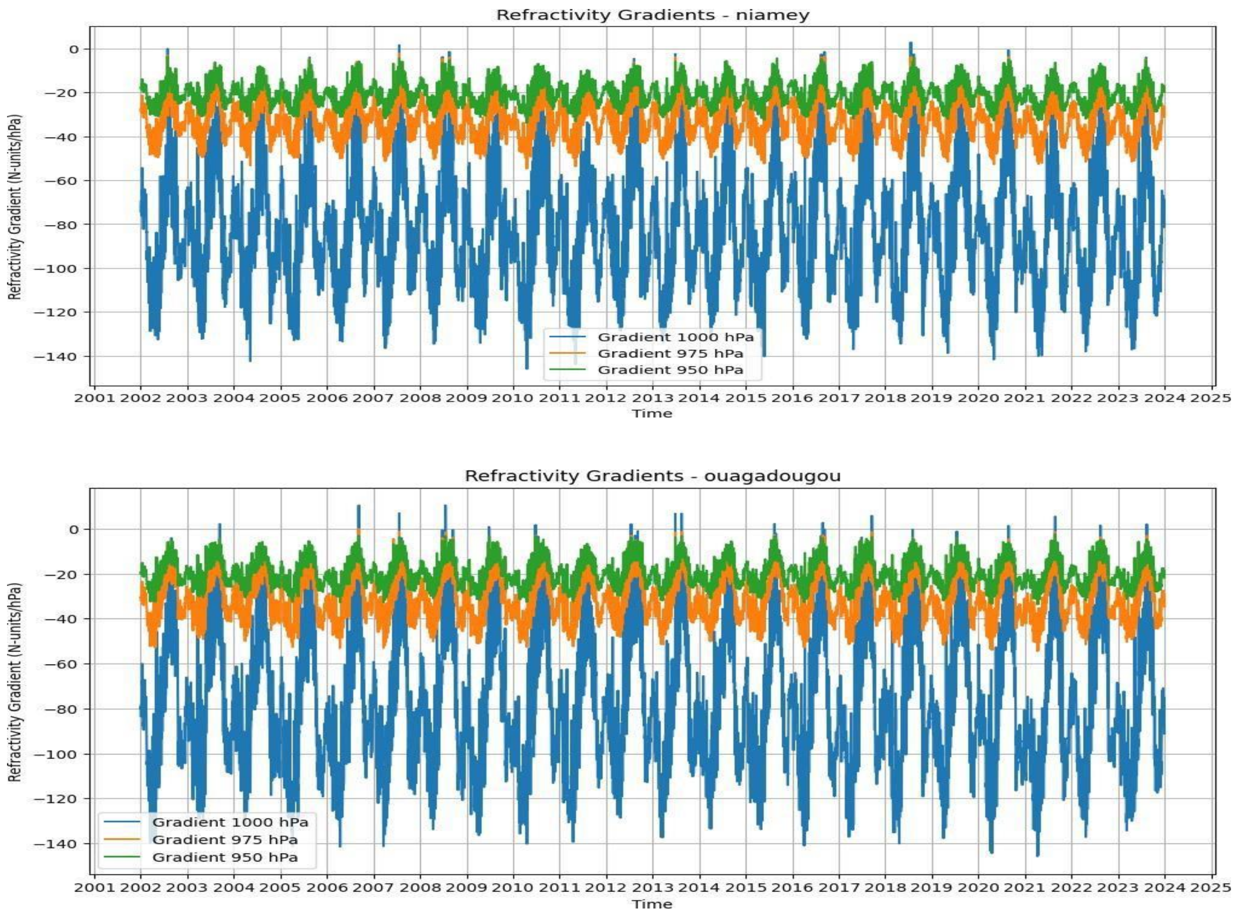


Figure 9a & 9b: "Refractivity gradient profiles in desert zones: (a) Niamey and (b) Ouagadougou, with strong gradients at 1000 hPa

3.3 Propagation Conditions Across Climatic Zones

Figure 10 presents a comprehensive analysis of refractivity gradient statistics across all study locations. The analysis revealed that tropospheric ducting (dN/dh < -157 N-units/km) was the predominant propagation condition at the 1000 hPa level for most locations, with the exception of Monrovia, where sub-refraction conditions were more prevalent at both 1000 hPa and 975 hPa levels.

Atmospheric ducting was particularly pronounced in savanna and desert regions (Niamey and Ouagadougou), which can be attributed to the presence of dry air layers and temperature inversions characteristic of these climatic zones. Dry air has a lower refractive index than moist air, and when combined with temperature inversions commonly found in desert regions, creates favourable conditions for strong refractive index gradients that trap radio waves within specific atmospheric layers.The coastal locations (Dakar, Freetown, Accra, and Monrovia) and tropical rainforest areas (Abidjan and Douala) also experienced significant ducting events, but these were more commonly associated with humidity gradients rather than temperature inversions. In coastal areas, the interface between maritime and continental air masses creates sharp humidity transitions that can trap radio waves, allowing them to travel over extended distances (Appendix I shows this propagation conditions).

Figure 10: Statistical distribution of refractivity gradients across all study locations, highlighting dominant propagation conditions

3.4 Seasonal and Diurnal Variations of Refractivity Gradient

3.4.1 Tropical Rainforest Zone

Figures 11a, 11b, and 11c illustrate the seasonal and diurnal variations of refractivity gradient in Abidjan (tropical rainforest) at 1000 hPa, 975 hPa, and 950 hPa respectively. At 1000 hPa, atmospheric ducting conditions (dN/dh < -157 N-units/km) prevailed throughout all seasons and times of day. However, at 975 hPa and 950 hPa, the predominant condition shifted to super-refraction (-157 < dN/dh < -40 N-units/km) this is in accordance with Adediji's research on average values of refractivity, refractivity gradient, and k-factor over Akure, a tropical zone of South-Western Nigeria, where 366 N-units, -51.36 N/km, and 1.51 respectively, indicating a super-refractive propagation condition in that area [5].

A distinct annual cycle was observed, with the dry season (December to February) experiencing more negative gradient values, such as -102.90 N-units/km at 950 hPa in February, compared to -81.57 N-units/km in September during the wet season. This seasonal variation can be attributed to the presence of drier air with lower moisture content during the dry season, resulting in steeper refractivity gradients [10].

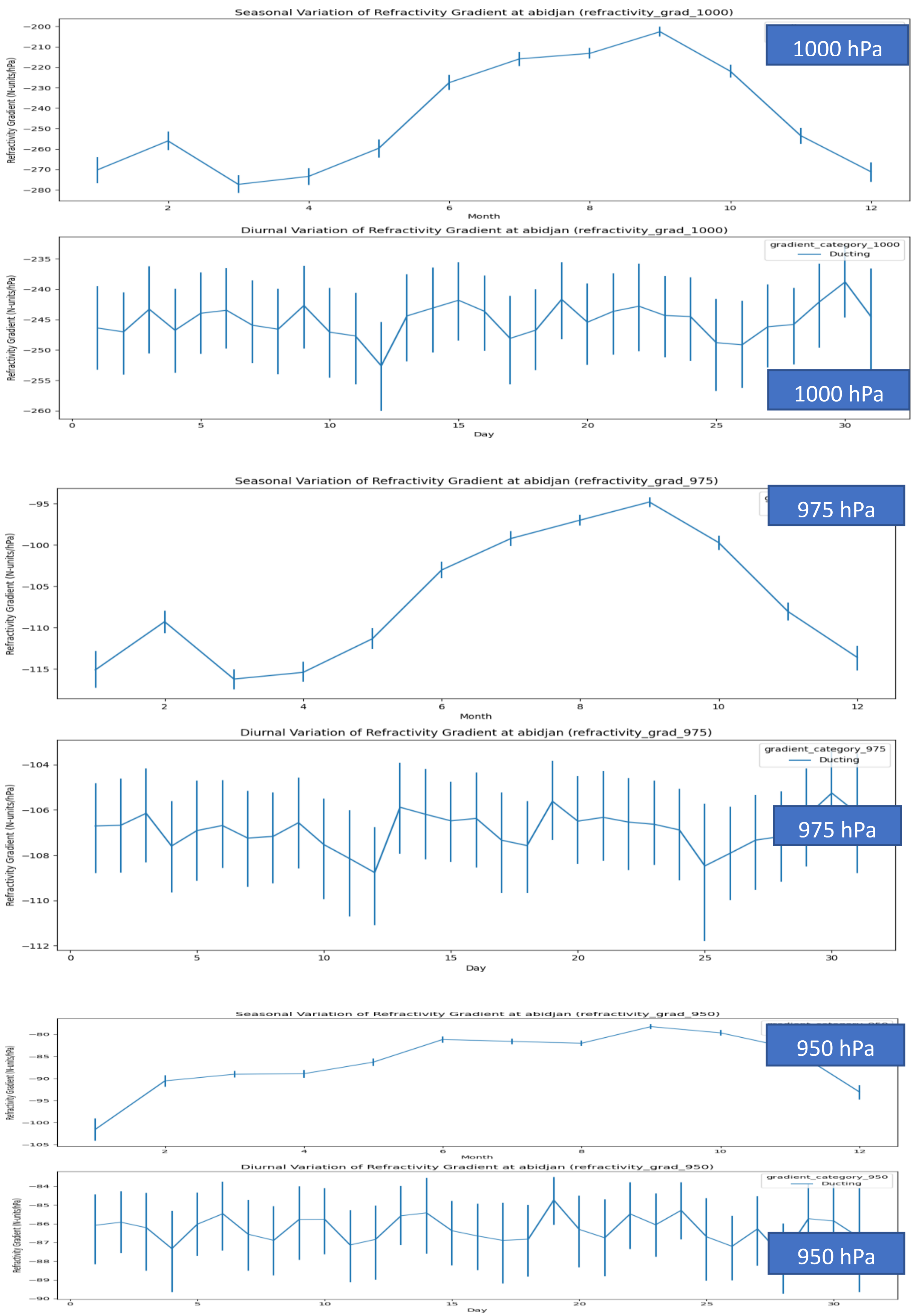


Figure 11a–c: Seasonal and diurnal refractivity gradient variations in Abidjan (rainforest) at: (a) 1000 hPa, (b) 975 hPa, and (c) 950 hPa

3.4.2 Coastal Zone

The seasonal and diurnal variations of refractivity gradient in Accra (coastal zone) are presented in Figures 12a, 12b, and 12c. Similar to the rainforest zone, atmospheric ducting was predominant at 1000 hPa throughout the year, while super-refractive conditions prevailed at 975 hPa and 950 hPa. The dry season exhibited more negative gradient values (-100.90 N-units/km at 950 hPa in March) compared to the wet season (-71.97 N-units/km at 950 hPa in August).

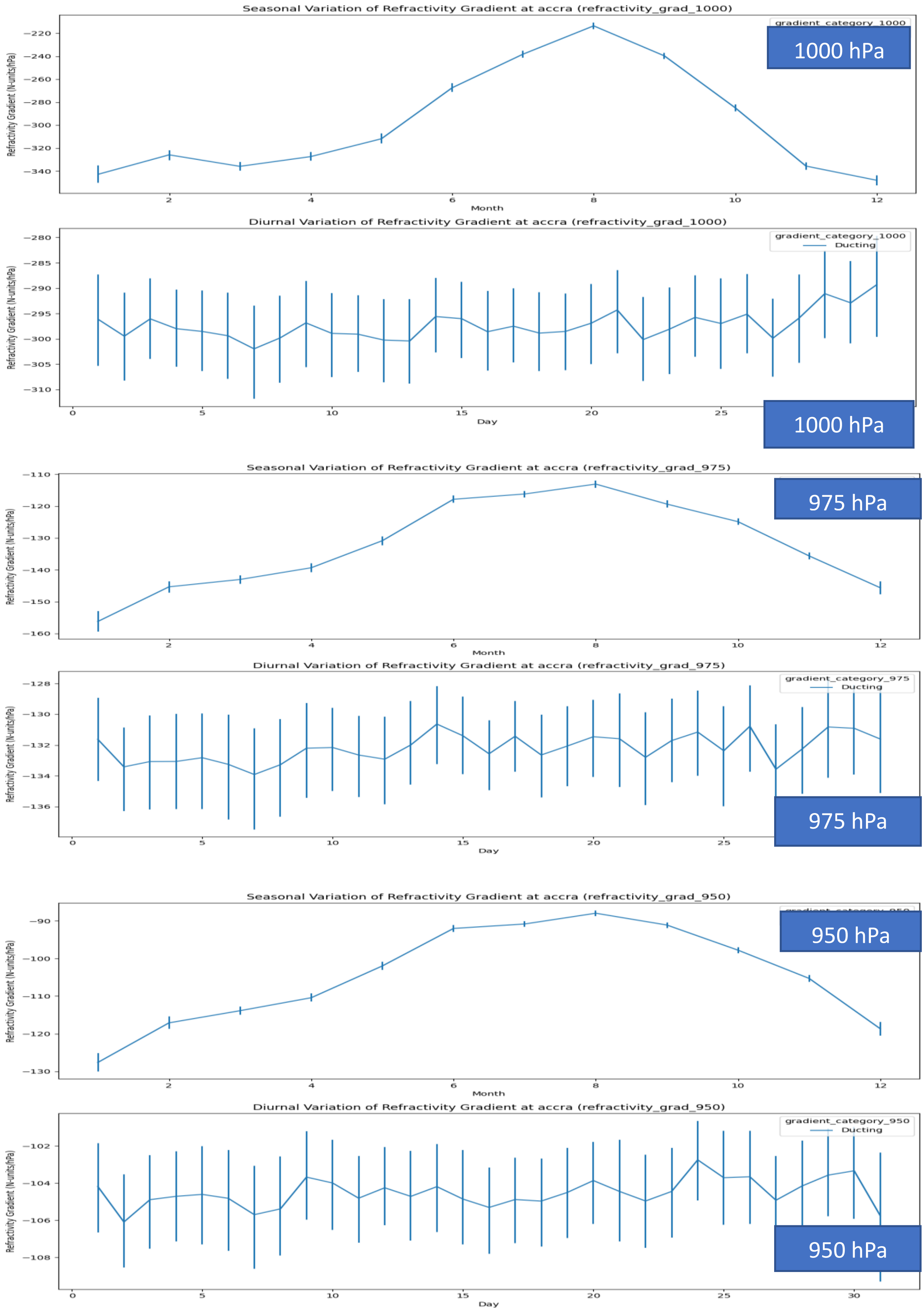


Figure 12a–c: Seasonal and diurnal refractivity gradient variations in Accra (coastal) at: (a) 1000 hPa, (b) 975 hPa, and (c) 950 hPa

3.4.3 Savanna Zone

Figures 13a, 13b, and 13c show the seasonal and diurnal variations of refractivity gradient in Mopti (savanna zone). All three pressure levels exhibited atmospheric ducting conditions throughout the day. However, during the peak rainy season, super-refractive conditions were observed at 975 hPa and 950 hPa, with refractivity gradient values of approximately -140 N-units/km at 975 hPa in August and -102 N-units/km at 950 hPa in September.

The most negative refractivity gradient values occurred in November and December, with the least negative values observed during the peak rainy season (July and August). This pattern reflects the pronounced seasonal transitions characteristic of savanna climates, with distinct wet and dry seasons affecting atmospheric stability and moisture content. This is in accordance with Ogunjo and Fuwape's research in exploring complex dynamics of radio refractivity which shows that higher refractivity gradients especially during the rainy season, indicate higher level of chaoticity [10].

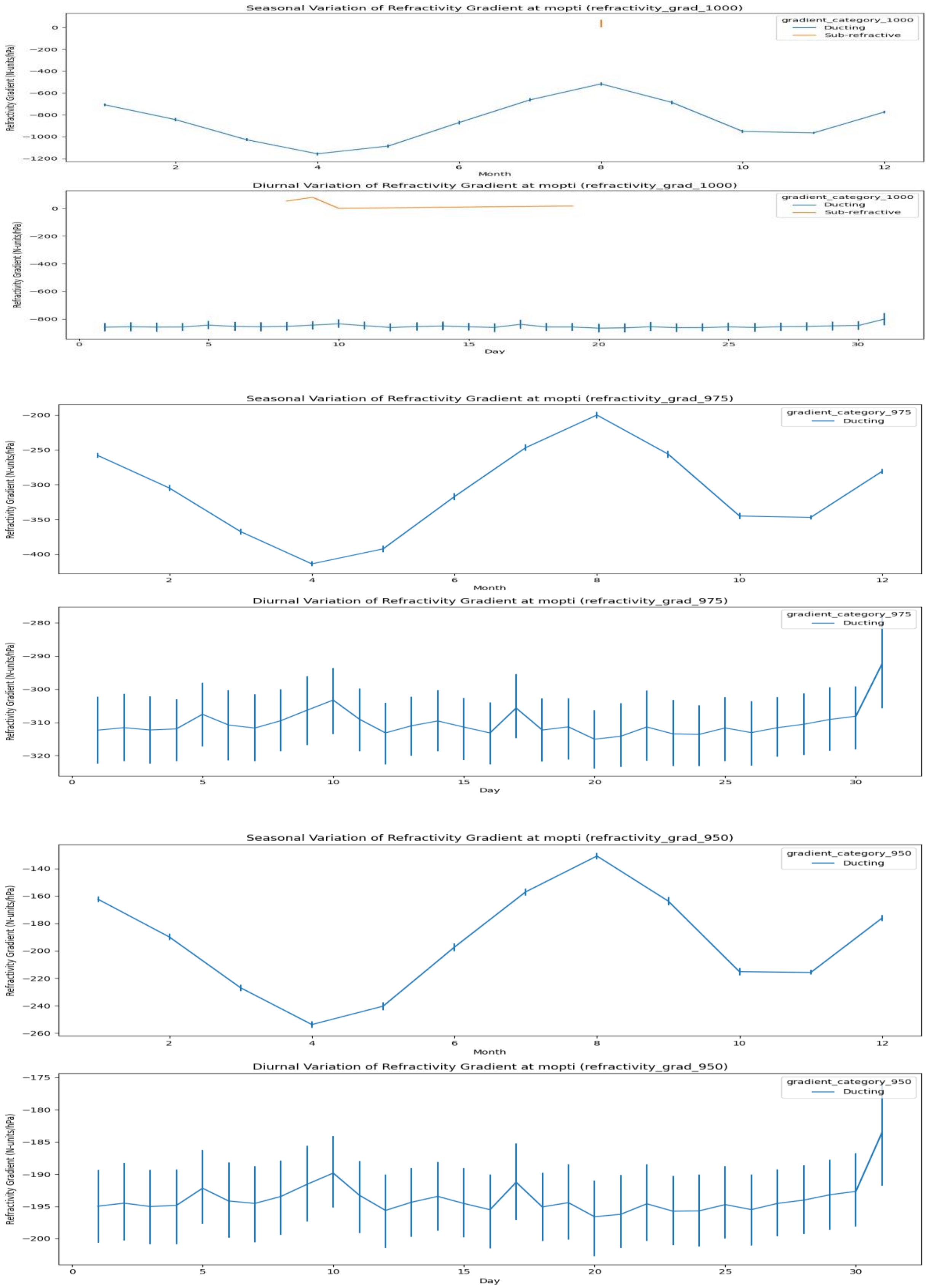


Figure 13a–c: Seasonal and diurnal refractivity gradient variations in Mopti (savanna) at: (a) 1000 hPa, (b) 975 hPa, and (c) 950 hPa

3.4.4 Desert Zone

The seasonal and diurnal variations of refractivity gradient in Niamey (desert zone) are illustrated in Figures 14a, 14b, and 14c. Similar to the savanna zone, atmospheric ducting conditions prevailed at all three pressure levels throughout the day. However, during the peak rainy season, super-refractive conditions were observed specifically at 950 hPa, with a refractivity gradient of approximately -139 N-units/km in August.

The desert zone exhibited the most extreme variations in refractivity gradient between seasons, reflecting the dramatic changes in atmospheric conditions between the brief rainy season and the prolonged dry period. The strong temperature inversions and dry air characteristics of desert environments create ideal conditions for radio wave trapping, contributing to the predominance of ducting conditions observed throughout most of the year.

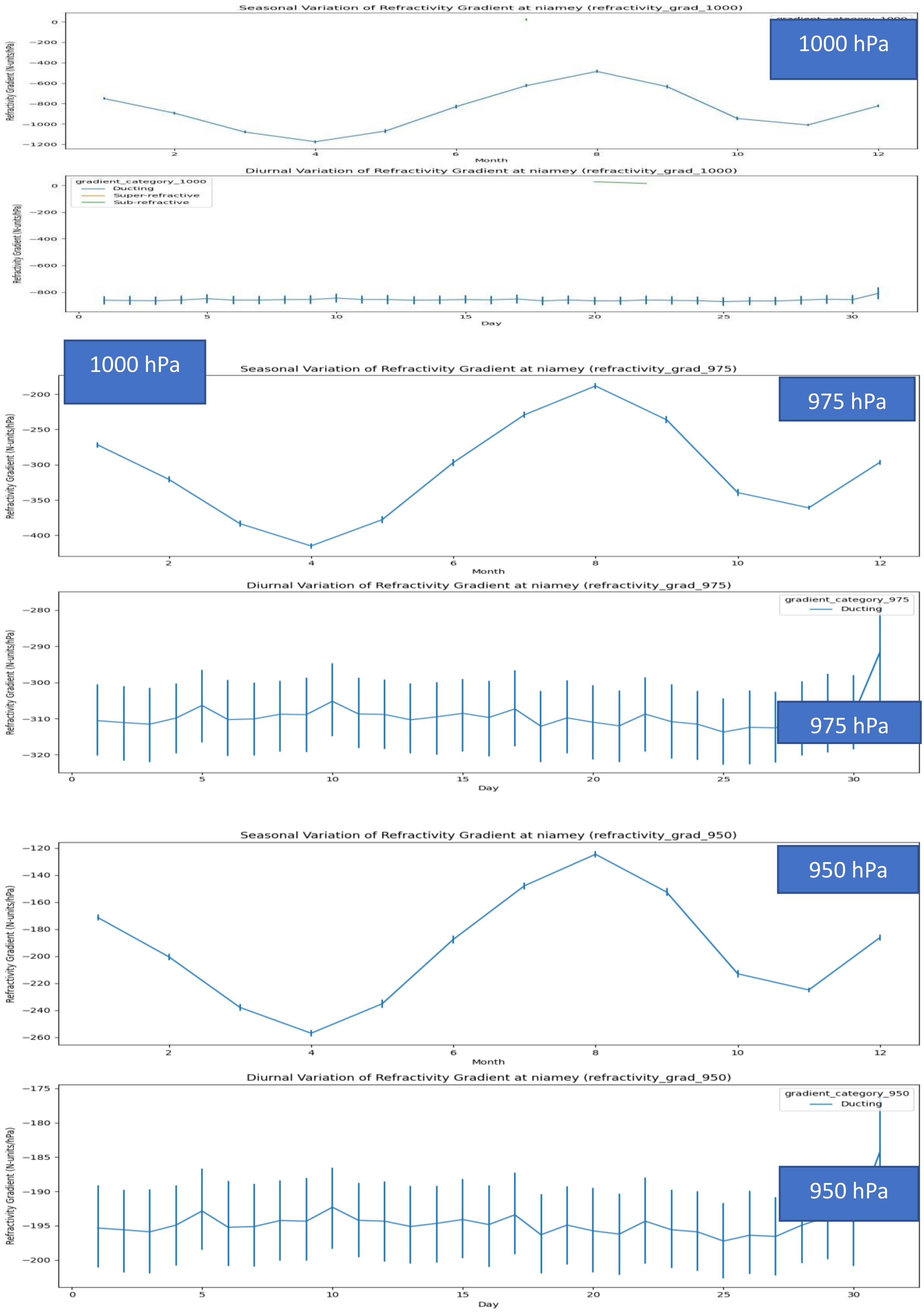


Figure 14a–c: Seasonal and diurnal refractivity gradient variations in Niamey (desert) at: (a) 1000 hPa, (b) 975 hPa, and (c) 950 hPa

3.5 Implications for Microwave Communication Systems

The observed patterns of refractivity and refractivity gradient across different climatic zones in West Africa have significant implications for the design and performance of microwave communication systems in the region:

1. **Ducting conditions** prevalent at the 1000 hPa level (approximately 110 m above ground) can extend communication ranges well beyond line-of-sight, but may also introduce interference issues between normally isolated communication systems.
2. **Super-refractive conditions** at higher altitudes (975 hPa and 950 hPa) indicate that radio waves will bend toward the Earth's curvature, potentially improving coverage for terrestrial systems but requiring careful planning to mitigate interference.
3. **Seasonal variations** in refractivity gradients suggest that communication system parameters may need seasonal adjustments to maintain optimal performance, particularly in savanna and desert regions where the differences between wet and dry seasons are most pronounced.
4. **Diurnal variations**, though less significant than seasonal changes, may affect signal quality during specific times of day, particularly in coastal areas where land-sea breeze cycles create daily fluctuations in atmospheric humidity profiles.
5. **Spatial variations** across climatic zones indicate that communication system designs must be tailored to specific regional conditions rather than applying uniform parameters across West Africa.

These findings underscore the importance of incorporating refractivity data into link budget calculations and system design specifications for microwave communication networks in West Africa.

4. Conclusion

This study has comprehensively analyzed radio refractivity and refractivity gradient variations across different climatic zones in West Africa using 22 years of reanalysis meteorological data. The key findings can be summarized as follows:

1. Surface refractivity exhibited distinct temporal patterns across all climatic zones, with values ranging from 372 to 419 N-units. Coastal and rainforest zones generally maintained higher refractivity values compared to savanna and desert regions, reflecting their characteristic higher humidity levels.
2. Refractivity gradient consistently decreased (became more negative) with increasing altitude across all study locations, indicating a systematic change in radio wave propagation conditions with height.
3. Tropospheric ducting emerged as the predominant propagation condition at the 1000 hPa level for most locations, while super-refractive conditions prevailed at 975 hPa and 950 hPa levels. Monrovia uniquely exhibited sub-refraction as the dominant condition at 1000 hPa and 975 hPa.
4. Savanna and desert regions demonstrated the strongest ducting conditions, attributed to dry air layers and temperature inversions characteristic of these climatic zones.
5. Significant seasonal variations in refractivity gradient were observed across all climatic zones, with the dry season generally exhibiting more negative gradient values than the wet season.

These findings contribute to a deeper understanding of radio wave propagation mechanisms in West Africa and provide valuable information for optimizing microwave communication system design and performance across the region's diverse climatic zones. Future research should incorporate direct measurements of refractivity profiles using radiosonde data to validate and refine the reanalysis-based results presented in this study.

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5.Appendix

Appendix 1: Percentage Occurrence of Different Propagation Conditions at Various Pressure Levels

Location	**Climatic Zone**	**Pressure Level (hPa)**	**Sub-refraction (%)**	**Standard (%)**	**Super-refraction (%)**	**Ducting (%)**
Dakar	Coastal	1000	12.4	19.7	21.5	46.4
		975	18.6	24.3	42.5	14.6
		950	22.1	35.6	37.8	4.5
Abidjan	Rainforest	1000	8.3	15.2	18.7	57.8
		975	14.5	21.8	54.2	9.5
		950	19.6	29.7	48.3	2.4
Kano	Savanna	1000	7.1	12.5	16.3	64.1
		975	13.9	18.4	38.6	29.1
		950	18.7	25.9	45.2	10.2
Niamey	Desert	1000	5.3	10.8	14.2	69.7
		975	11.6	15.2	32.8	40.4
		950	16.2	22.5	39.7	21.6

Appendix 2: Seasonal Mean Refractivity Gradient (N-units/km) at Different Pressure Level.

Climatic Zone	**Location**	**Pressure Level**	**Dry Season**	**Transition Season**	**Wet Season**
Coastal	Accra	1000 hPa	-187.4	-172.8	-161.5
		975 hPa	-103.2	-96.5	-89.7
		950 hPa	-95.6	-88.3	-72.0
Rainforest	Abidjan	1000 hPa	-192.8	-183.7	-168.2
		975 hPa	-112.6	-104.3	-93.6
		950 hPa	-102.9	-91.5	-81.6
Savanna	Mopti	1000 hPa	-206.5	-197.3	-185.7
		975 hPa	-148.7	-138.4	-124.6
		950 hPa	-118.5	-109.7	-102.0
Desert	Niamey	1000 hPa	-212.3	-201.6	-192.4
		975 hPa	-153.6	-144.8	-139.2
		950 hPa	-132.7	-122.3	-110.5