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Research Paper

INTER-ANNUAL VARIATION OF SURFACE REFRACTIVITY IN DRY AND WET MONTHS OVER WEST AFRICA

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In this paper, satellite-based meteorological data were employed in the estimation of surface refractivity for different climatic zones over West Africa with a view to determining its annual variability in wet months (May-October) and dry months (November-April) over a period of 22 years. In this study, West Africa continental areas have been partitioned into four climatic zones: Mangrove Rain Forest (below latitude 5^0N); Tropical Rain Forest (within 5^0N and 10^0N); Guinea Savannah (within 10^0N and 15^0N); and Sudan Sahel (within 15^0N and 20^0N). The Surface Meteorology and Solar Energy (SSE) dataset used for this study were satellite and model-based products covering 36 meteorological stations in four climatic zones across West Africa. The seasonal pattern of surface refractivity and its related parameters were found to be associated with the migration of the Inter Tropical Discontinuity (ITD), the fluctuations of which dictate and control the rainfall and water vapor profiles characteristics over West Africa. The climatic zones over West Africa at 2 m had annual surface refractivity ranging between 6 N-units and 9 N-units over the period of 1983-2005. At 10 m; climatic zones 1 and 2 had the same average of 269 N-units; average of 263 N-units was observed at zone 3 and 260 N-units at zone 4. Annual variation of N in climatic zone 4 was 5 N-units in dry months and 14 N-units in wet months.

Keywords: Surface refractivity, Inter-Tropical Discontinuity (ITD), Climatic zones

INTRODUCTION

In the planning and design of microwave communication links, the structure of the radio refractive index in the lower part of the Atmospheric Boundary Layer (ABL) is very important. The propagation of radio wave signal in the troposphere is influenced by many weather processes such as temperature, pressure and humidity. This weather system resulted in the seasonal variation and weather variability from year to year over the tropical region. This variations in usually bring about abrupt changes insurface refractivity beginning from the lower atmosphere into troposphere. Multipath effecton

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communication signals can also occur as a result of large scale variations in atmospheric radio refractive index, such as different horizontal layers having different refractivity scenarios (Grabner and Kvicera, 2008).

This effect occurs most often, when the same radiowave signals follow different paths thereby having different time of arrivals at its targeted point. This often brings about interference of the radio wave signals with each other during propagation within the troposphere. Thus, the range of radiowave is determined by the height dependence of the refractivity.Thus, the refractivity of the atmosphere will not only vary with respect to height in the troposphere but also as weather pattern varies across the latitude (Okoro and Agbo, 2012).

The troposphere extends to an altitude of about 9 km at the north or south poles and 17 km near the equator. Most of the earth's weather activities occur in this layer. It is very turbulent due to the spatial and temporal variations of temperature, density, and pressure. The variations of these atmospheric parameters greatly affect radiowave propagation and other communication signals (Zou *et al.,* 2000). The prevailing tropospheric characteristics are usually taken into consideration in the design of communication equipment suitable for terrestrial propagation in a particular region. This is because the troposphere is very critical to transmission and reception of electromagnetic waves (Agunlejika and Raji, 2010). The cost of setting-up meteorological stations limits the measurement coverage and contiguous acquisition of meteorological parameters required for surface refractivity studies over West Africa. In this paper, satellite-based meteorological parameters were employed in the estimation of surface refractivity over West Africa with a view to determine its annual variability in dry months (November-April) and wet months (May-October) over a period of 22 years.

THEORETICAL BACKGROUND FOR ESTIMATING OF SURFACE REFRACTIVITY

Surface refractivity may be determined in a number of ways, either directly (using a refractometer), or indirectly through the measurements of temperature, pressure and humidity (Diodato and Bellochi, 2007). Recent improvements in technology have also permitted the use of Light Detection and Ranging (LIDAR) measurement systems. Pulses of radiation are fired from a laser, and the radiation backscattered by atmospheric gases and particles is measured. The Raman LIDAR technique can measure water vapour and temperature profiles from the radiation emitted at the earth surface; it is therefore suited for sensing radio refractivity. However, while this method can yield high measurement accuracy, the cost of this equipment prohibits its widespread use (Hviid *et al.,* 1995).

Surface refractivity variations in the troposphere have been a subject of sustained interest because of its important role in microwave radio communication (Martin and Vaclav, 2003). The quality of signal reception and probability of the link failure in microwave communication systems are largely controlled by spatial and temporal variations of surface refractivity (Lam *et al.,* 2007). Line-of-Sight (LOS) microwave links may also experience severe fading, owing to refraction of the transmitted beam along its propagation path. Refractive fading can significantly impair service on terrestrial LOS microwave transmission systems. In coastal areas, surface refractivity changes are closely associated with the sea and land breezes, and super-refraction and ducting over the sea along the coast is most-marked when dry warm air from the adjacent land mass extends over a comparatively cooler sea (Judd, 1985).

Surface refractivity of air is a function of pressure, temperature and relative humidity. In the studies of surface refractivity, all the three parameters can be combined into one single parameter that facilitates the analysis and study some of the effects of meteorological factors on radiowave propagation at the higher frequencies like microwaves (Radha and Purnachandra, 2005). Radio waves travel through vacuum with a speed equal to the speed of light. In any other medium, the speed of the radio waves will be a ratio of the speed of light in vacuum (c) and the refractive index (n) of the medium (ITU-R, 2003). The value of ‘n’ for dry air is almost the same for radio waves and the light waves. But the ‘n’ of water vapor, which is always present in some quantity in the lower troposphere, is different for the light waves and radio waves. This arises from the fact that water vapor molecule has a permanent dipole moment which has different responses to the electric forces of different frequencies; at microwave frequencies water vapour molecules are subjected to electronic polarization (Radha *et al.,* 2003).

Hence, for these frequencies, the dielectric constant and the refractive index of water vapour is greater than that of dry air. The refractive index ‘n’ for moist air near the surface has the value of the order of 1.0003 and the variation in ‘n’ is only of the order of 10^4. The surface refractive, N, is defined in terms of ‘n’ (ITU-R, 2003) as

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

This enables the easy manipulation of refractivity valuewhich is of the order of 300 rather than ‘n’ which is an inconvenient number. A theory based on the molecular polarisation of the gases of the atmosphere enables the refractivity to be related to the temperature T in °K, to atmospheric pressure P in millibars and to water vapor pressure, e in millibars. The surface refractivity, N is expressed by awell known relation (ITU-R, 2003):

$$N = \frac{77.6}{T}\left[P + \frac{4180e}{T}\right] \qquad ...(2)$$

In terms of measured meteorological quantities, refractivity, N can be expressed as:

$$N = \frac{77.6P}{T} + 3.73\times 10^5 \frac{e}{T^2} \qquad ...(3)$$

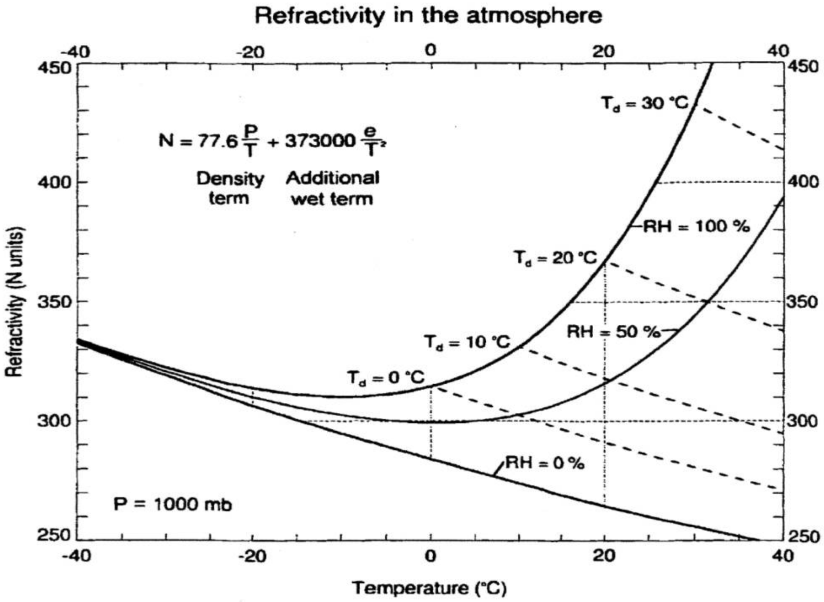
where: P = Atmospheric Pressure (hPa), e = water vapour pressure (hPa) and T = Absolute Temperature (K). Therefore, N is expressed as:

$$N = \frac{77.6}{T}\left[P + \frac{4180(e_s RH)}{T}\right] \qquad ...(4)$$

whereesis the saturation vapour pressure in millibars and RH is the relative humidity in percent (ITU-R, 2003).

The expression for the surface refractivity, N, may be regarded to consist of dry term and wet term. The dry term does not depend on humidity; it is proportional to the density of the air. The dry term is also referred to as pressure term. The wet term depends on moisture variation and it is responsible for the temporal and spatial variability of Surface Refractivity Index in the troposphere (as shown in Figure 1). The dry term decreases

Figure 1: Variation of Refractivity with Temperature and Relative Humidity [6]



with increase in temperature at constant pressure. The wet term increases with increase in relative humidity (ITU-R, 2001).

DATA SOURCE AND PROCEDURES OF ANALYSIS

In this work, the West Africa continental areas have been partitioned into four climatic zones (as shown in Table 1 and Figure 2). Meteorological data from thirty-six geo-referenced stations corresponding to World Meteorological ground stations across West Africa and comprising six stations in climatic zone 1; ten stations in zone 2; ten stations in zone 3; and ten stations in zone 4 were used in this study (as shown in Table 1). The stations were evenly distributed across the four climatic zones. A geo-referenced location map of the area under study was prepared showing station points across West African region.

The Surface Meteorology and Solar Energy (SSE) dataset used for this study aresatellite and model-based products (http://eosweb.larc.nasa.gov/sse). The long-term estimates of meteorological quantities and surface solar fluxes, which were specifically formulated by the National Aeronautical Space Administration (NASA) to aid the design and planning of communication systems, had been compared to ground site data on a global basis, and they were found to be sufficiently consistent to provide reliable solar and meteorological resource data over regions where surface measurements are sparse or nonexistent (Ducharne *et al.,* 2000).

Raw point datasets for 22 years including air temperature, relative humidity and atmospheric pressure at 2 m and 10 m, averaged daily with attributes of geographic features (longitude and latitude), were extracted from NASA meteorological databank through Notepad basic text editor using text import wizard to delimit the

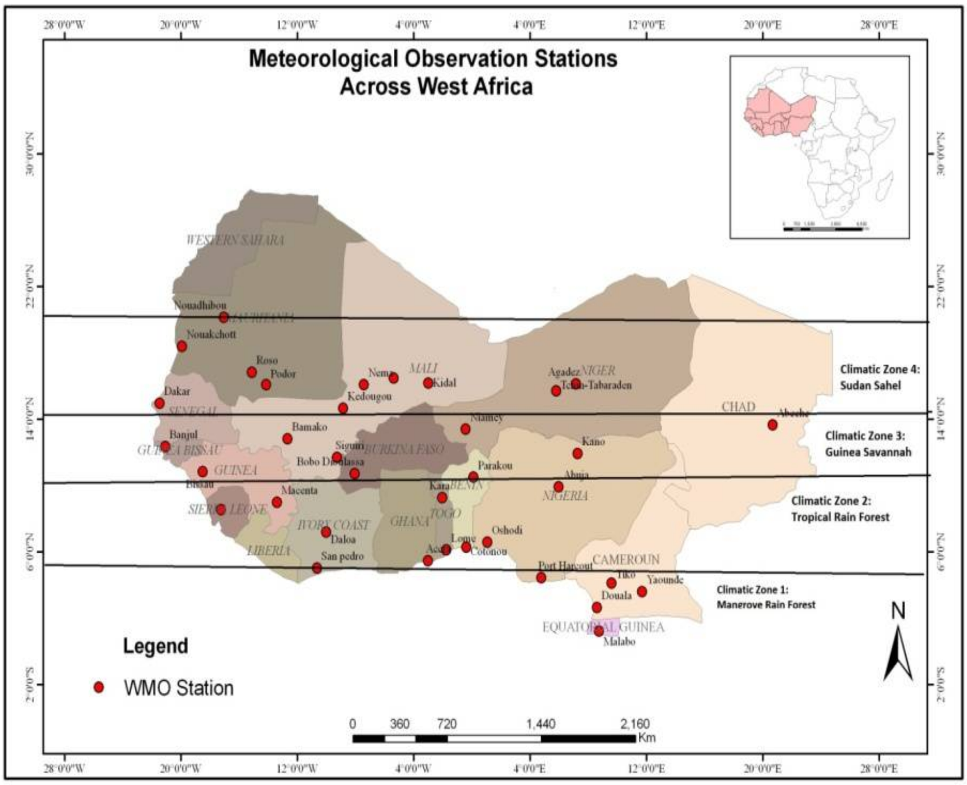
Table 1: Selected WMO Stations across West Africa

S. No.	Country	Location	Elevation (m)	Longitude	Latitude	WMO Index Number
CLIMATIC ZONE 1 (Mangrove Rain Forest) at Latitude < 5ºN						
1.	Nigeria	Port Harcourt	18	7.1E	4.85N	65250
2.	Cameroon	Yaounde	760	11.51E	3.83N	64950
3.	Cameroon	Douala	9	9.73E	4.0N	64910
4.	Cameroon	Tiko	52	9.36E	4.8N	64912
5.	Ivory Coast	San Pedro	30	6.65W	4.75N	65594
6.	Equatorial Guinea	Malabo	56	8.76E	3.75N	64810
CLIMATIC ZONE 2 (Tropical Rain Forest) at Latitude 5⁰N - 10ºN						
7.	Nigeria	Oshodi	19	3.21E	6.33N	65202
8.	Nigeria	Abuja	344	7.0E	9.25N	65125
9.	Benin Republic	Cotonou	9	2.38E	6.35N	65344
10.	Benin Republic	Parakou	393	2.61E	9.35N	65330
11.	Togo	Lome	25	1.25E	6.16N	65387
12.	Togo	Kara	341	1.16E	9.55N	65357
13.	Ghana	Accra	69	0.16W	5.6N	65472
14.	Ivory Coast	Daloa	277	6.46W	6.86N	65560
15.	Guinea	Macenta	543	9.46W	8.53N	61847
16.	Sierra Leone	Freetown	27	13.20W	8.61N	61856
CLIMATIC ZONE 3 (Guinea Savannah) at Latitude 10ºN – 15ºN						
17.	Guinea	Siguiri	366	9.16W	11.43N	61811
18.	Guinea Bissau	Bissau	36	15.65W	11.88N	
19.	The Gambia	Banjul	2	16.45W	13.45N	61711
20.	Senegal	Dakar	24	17.50W	14.73N	61641
21.	Senegal	Kedougou	167	12.21W	12.56N	61699
22.	Mali	Bamako	381	7.95W	12.53N	61291
23.	Niger Republic	Niamey	227	2.16E	13.48N	60152
24.	Burkina Faso	Bobo-Dioulassa	460	4.31W	11.16N	65510
25.	Chad	Abeche	549	20.85E	13.85N	64756
26.	Nigeria	Kano	481	8.53E	12.5N	65046

Table 1 (cont.)

S. No.	Country	Location	Elevation (m)	Longitude	Latitude	WMO Index Number
CLIMATIC ZONE 4 (Sudan Sahel) at Latitude > 15ºN						
27.	Mali	Kidal	459	1.35E	18.43N	61214
28.	Mali	Tombouctou	264	3.0W	16.71N	61223
29.	Mauritania	Nouakchott	3	15.95W	18.10N	61442
30.	Mauritania	Nema	269	7.26W	16.60N	61497
31.	Mauritania	Nouadhibou	3	17.3W	20.93N	61415
32.	Mauritania	Roso	6	15.81W	16.50N	61489
33.	Senegal	Podor	7	14.96W	16.65N	61612
34.	Niger Republic	Tchin-Tabaraden		5.48E	15.43N	61028
35.	Niger Republic	Agadez	502	7.98E	16.96N	61024
36.	Niger Republic	Bilma	355	12.55E	18.41N	61017

Figure 2: Map of West Africa showing the Study Location



general data format into numeric values and number. The data were assembled together in created attribute table. The data contained three variables including atmospheric pressure at 2 m and 10 m, temperature at 2 m and 10 m, and relative humidity at 2 m and 10 m. Data covering thirty-six meteorological stations in four climatic zones across West Africa within Latitude 3^o and 20^oN were used for the study.

The annual mean of surface refractivity for each year was estimated using

$$N = 1/x\Sigma N_i \qquad ...(5)$$

where i = 1, …, x and x = 365

The annual mean value of surface refractivity in the dry months (November-April) was estimated using

$$N = 1/x\Sigma N_i \qquad ...(6)$$

where i = 1, …, x and x = 181

The annual mean value of surface refractivity in the wet months (May-October) was estimated using

$$N = 1 / x\Sigma N_i \qquad ...(7)$$

ANNUAL VARIATION OF SURFACE REFRACTIVITY AT 2 M AND 10 M FOR DIFFERENT CLIMATIC ZONES ACROSS WEST AFRICA

Figures 3 and 4 showed the annual averages of N from 1983 to 2005 at 2 m an,d 10 m respectively across different climatic zone over West Africa. At 2 m, climatic zone 1 had the largest range between 309 N-units – 318 N-units, and followed by zone 3 with a range between 301 N-units – 308 N-units. Zone 2 had a range between 283 N-units – 289 N-units and zone 4 had a range between 290 N-units – 297 N-units. In Figure 3, the crests on the graphs were indicators of wet years and the troughs were indicators of dry years. Weather report showed that 1998 was one of the warmest years in history with severe storm occurrence in West Africa. The annual averages were unpredictable as to whether the degree of dryness or wetness in the following year will increase or decrease; however, the range of

Figure 3: Annual Variation of Surface Refractivity (N) at 2 m for different Climatic Zones across West Africa (1983 - 2005)

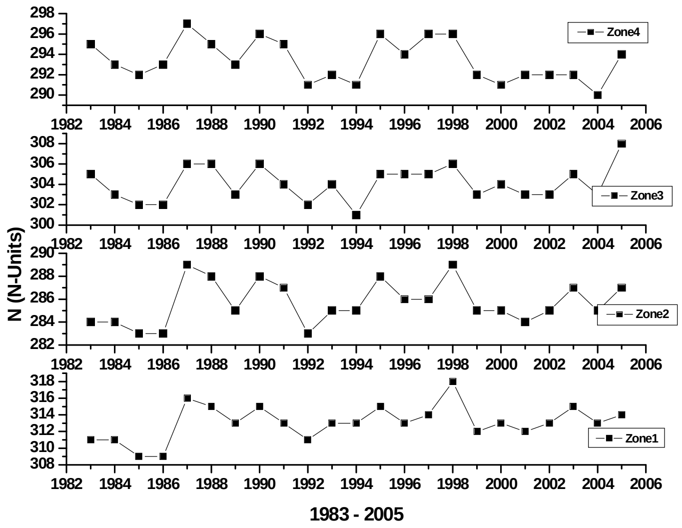
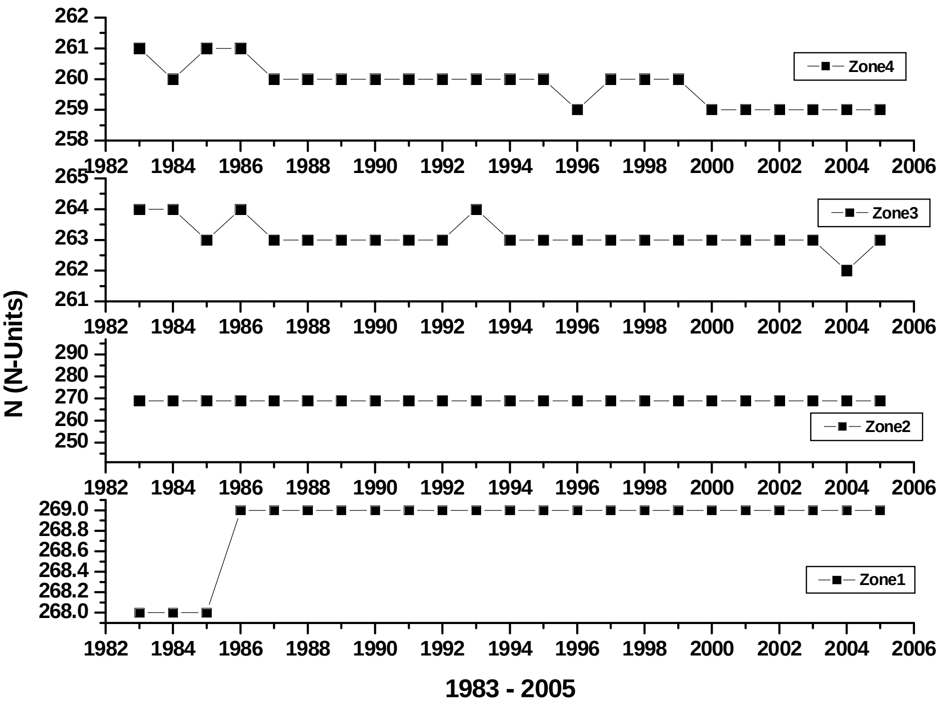


Figure 4: Annual Variation of Surface Refractivity (N) at 10 m for different Climatic Zones across West Africa (1983 - 2005)



annual variation from 1983 – 2005 provides a guide for future projections.

The wet years were marked with high intensity and long duration of rainfall while the dry years have low intensity and short duration of rainfall. The degree of wetness or dryness in the climatic zones over the years can be deduced from annual variation of N. The climatic zones 1 to 4 had a range of 6 N-Units to 9 N-units within the period of 1983 - 2005, zone 1 had the mean and standard deviation of 313±5 N-units, zone 2 had 286±3 N-units, zone 3 had 304±4 N-units, and zone 4 had 293±4 N-units. These are useful findings from annual averages of N, this can be employed for prediction and modeling of spatial and temporal variability of surface refractivity over West Africa at 2 m.

In Figure 4, the annual averages of N at 10 m were almost constant over the years. Even distribution of seasonal weather elements, most especially temperature and moisture, in climatic zones across West Africa at 10 m was responsible for marginal range of N. The average annual value of N in climatic zones 1 and 2 was 269 N-units, zone 3 was 263 N-units and zone 4 was 260 N-units. Annual averages of N were relatively stable at 10 m across West Africa except for climatic zones 3 and 4 where the intensity and duration of rainfall were more erratic.

ANNUAL VARIATION OF SURFACE REFRACTIVITY IN DRY AND WET MONTHS FOR DIFFERENT CLIMATIC ZONES ACROSS WEST AFRICAN

The annual averages of N in the dry and wet months from 1983 – 2005 were shown in Figures

Figure 5a: Annual Variation of Surface Refractivity (N) in Dry (Nov - Apr) and Wet (May - Oct) Months for Climatic Zone 1 across West Africa

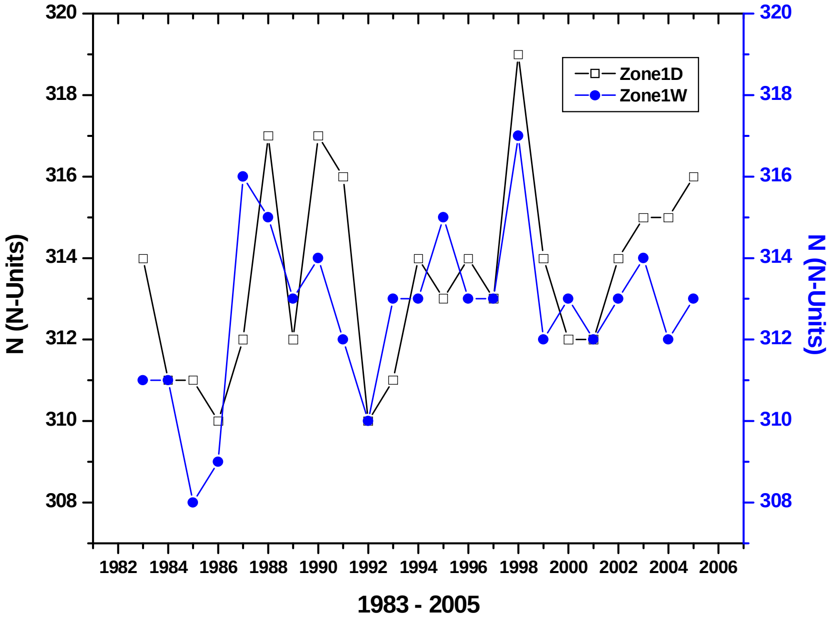
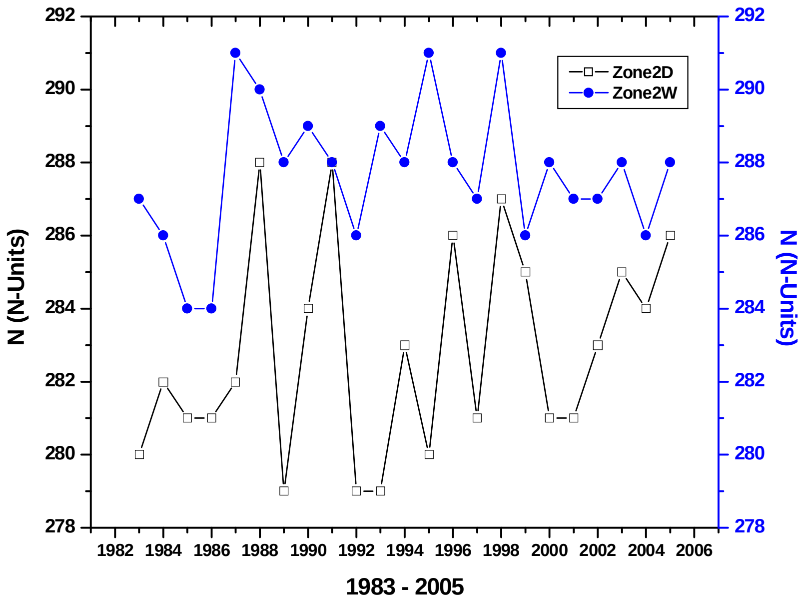


Figure 5b: Annual Variation of Surface Refractivity (N) in Dry (Nov - Apr) and Wet (May - Oct) Months for Climatic Zone 2 across West Africa



5a – 5d. In the dry months, zone 1 had a widest range of N between 310 N-units – 319 N-units. In wet months, zone 4 had a widest range of N between 308 – 322 N-units. Zone 4 had the least range of N in dry months (5 N-units) and the highest annual range of N in wet months (14 N-units). In figure 5d, zone 4 was mostly under the influence of dry and dust-laden northeasterly

Figure 5c: Annual Variation of Surface Refractivity (N) in Dry (Nov - Apr) and Wet (May - Oct) Months for Climatic Zone 3 across West Africa

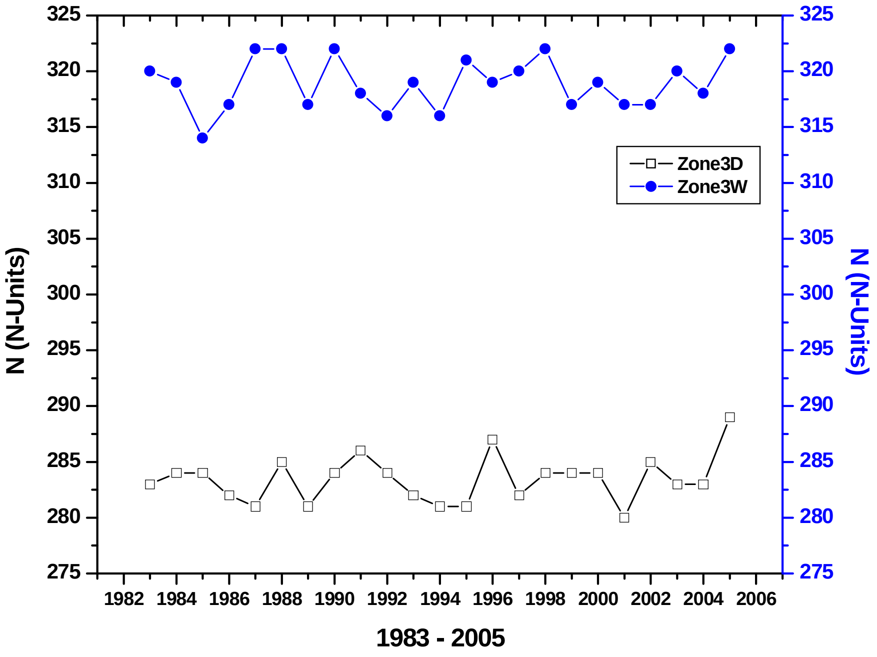
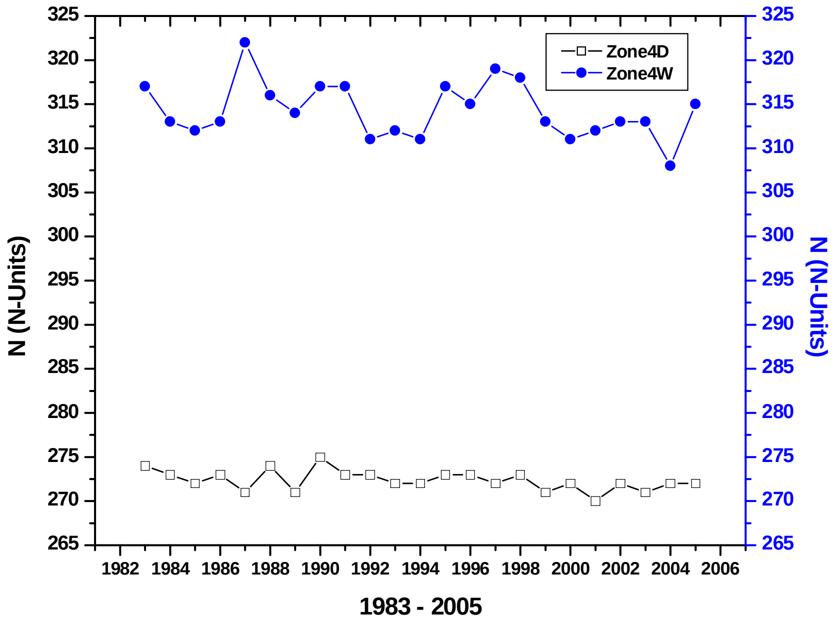


Figure 5d: Annual Variation of Surface Refractivity (N) in Dry (Nov - Apr) and Wet (May - Oct) Months for Climatic Zone 4 across West Africa



tropical airmass with the characteristic of very low moisture and high temperature in the dry months. This is responsible for the lowest values of N observed in zone 4 in the dry months and the values are very consistent over the years except for a period between 1987 and 1990.

In Figure 5a, zone 1 had equal range of N (9 N-Units each) in dry and wet months, this indicates the continuous influence of the coast and a well-defined rainfall regime in the zone over the years. The increase/decrease in wetness in each year had a strong influence on the increase/ decrease of N values both in the dry and wet months. The years with increase in wetness, such as 1987, 1988, 1990, 1998 and 2003, also experienced increase in N values both in dry and wet months. The years with decrease in wetness, such as 1986, 1989, 1992, 1997 and 2000, also experienced decrease in N values both in dry and wet months. In climatic zone 1 (0 – 5^0N), the probability of increase/decrease in values of N for wet months can be determined from the values obtained in dry months.

In Figure 5b, zone 2 had the least annual averages of N in both the wet and dry months; this is a transition zone from very wet climate to moderately wet climate. There is a gradual decrease in moisture in the inland stations throughout the year. This zone also had a characteristic similar to what was observed in zone 1. The decrease/increase in wetness moderately influenced the decrease/increase in N values from year to year. Years with increase in wetness such as 1987, 1998 and 2003 slightly followed the trend in zone 1. Years with decrease in wetness such as 1986, 1989, 1992, 1997, and 2004 also recorded decrease in N values both in dry and wet months. In Figure 5c, zones 3 had equal annual range of N in dry and wet months (9 N-units) as recorded in zone 1. There was a clear departure in annual trend of N values in dry and wet months from what was observed in zones 1 and 2. However, the influence of increase/ decrease in wetness from year to year slight influenced dry and wet months in 1988, 1989, 1995, 1996, and 2004. The annual averages of N values in dry and wet months from year to year showed that the climatic zone was characterized by two distinct seasons: the zone significantly represent a transition zone between wet and dry climate (10 – 15^oN). The rainy season characterized by humid southwesterly maritime airmass, and the dry season characterized by the harmattan, a dry, dust laden wind which usually pushes south from the Sahara desert into the sub region in November and retreats in March.

In Figure 5d, a wide gap between the values of N in dry and wet months was observed throughout the period under consideration. The minimum and maximum difference was 38 N-units and 47 N-units respectively. The annual averages of N from year to year during the wet months extremely varied and this depicted unpredictable rainfall pattern which characterized the areas beyond latitude 15^0N across West Africa. The N values in zone 4 indicated extremely low moisture/temperature in the dry months and high temperature with moderate increase in moisture in the wet months.

In Figures 5a – 5d, the annual averages of surface refractivity in dry and wet months for different zones were observed to represent weather pattern peculiar to each zone across West Africa. Moisture was substantial even in dry months in zones1 and 2; the influence of southwest monsoon from the Atlantic was noticed in the zones during the dry months. The relative humidity was slightly lower in dry months as it was in the wet months. In climatic zones 3 and 4, a wide gap was noticed between annual averages in dry months and wet months. Wet months in the zones are very short as the peak of rainy season was observed in July/August when ITD is at the northern most location. The dry months, in climatic zones 3 and 4, were characterized by clear skies, moderate daily temperatures and low humidity, this accounted for low values of surface refractivity in dry months.

The seasonal pattern of surface refractivity is associated with the north – south migration of ITD. The movement determines rainfall regimes and water vapor profiles across the region. The annual averages of N in dry and wet months for different climatic zones across West Africa showed the degree of wetness or dryness in each zone from year to year as well as the contributions of meteorological parameters responsible to the observed N variations in each zone. In zone 1, N had equal annual range in the dry and wet months; this is an indication that there was no significant change in relative humidity throughout the year. There was a slight change in climatic zone 2, N in wet months was slightly higher than that of dry months; this is an indication of a slightly lower relative humidity values in the dry months than wet months. The gap in values of N in dry and wet months was widened in zone 3 and became wider in zone 4. The variation showed a clear pattern of climate characteristics across West Africa.

CONCLUSION

The seasonal pattern of surface refractivity and its related parameters are associated with the migration of the Inter Tropical Discontinuity (ITD), which also determines the rainfall and water vapor profiles characteristics across the region.The climatic zones over West Africa at 2 m had annual surface refractivity range between 6 N-units and 9 N-units over the period of 1983 – 2005. At 10 m; climatic zones 1 and 2 had equal annual average of 269 N-units; annual range of 263 N-units was observed at zone 3 and 260 N-units at zone 4. Annual variation of N in climatic zone 4 was 5 N-units in dry months and 14 N-units in wet months.

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