Variations of Surface Refractivity for Different Climatic Zones across West Africa

Ajileye, O. O[1], Jegede, O. O[2], Ayoola, M. A[2], Eguaroje, O. E[1] and Mohammed, S. O[3]

Abstract

Temporal variations in surface refractivity, N, in the lower part of the atmosphere is an important parameter in the study of micro-meteorology and in planning of terrestrial communication links. Previous studies across West Africa on surface refractivity were based on extrapolated data from radiosonde measurements which lacked the required resolution and coverage necessary for the investigations of spatial and temporal variations of surface refractivity across West Africa particularly in the lower atmosphere. In this study, West Africa continental areas have been partitioned into four climatic zones: Mangrove Rain Forest (below latitude 5°N); Tropical Rain Forest (within 5°N and 10°N); Guinea Savannah (within 10°N and 15°N); and Sudan Sahel (within 15°N and 20°N). The Surface Meteorology and Solar Energy (SSE) dataset used for this study are satellite and model-based products covering thirty-six meteorological stations in four climatic zones across West Africa within Latitude 3° and 20°N. 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 within a period of 22 years (1983 – 2005). The results showed that the range of deviation was determined by seasonal moisture distribution. Seasonal variation of surface refractivity in climatic zones 1 and 2 showed similar trends of bimodal pattern and a deep in August due to short break in rainfall. Surface refractivity values were generally low during the dry months and high during the wet months. Surface refractivity was observed to have higher values at 2 m than 10 m. The maximum of 326 N-Units and 300 N-Units were recorded in April while the minimum of 300 N-Units and 261 N-Units were recorded in January for zones 1 and 2 respectively. Maximum values of 332 N-Units and 336 N-Units were recorded in June and July for climatic zones 3 and 4 while minimum of 272 N-Units and 269 N-Units were recorded in December and January respectively

1.0 Introduction

Temporal variations in surface refractivity, N, at the lower part of the atmosphere is an important parameter in the study of micro-meteorology and in planning of terrestrial communication links. It is defined as a ratio of the radio wave propagation velocity in free space to its velocity in a specified medium. The process of radio wave communication involves propagation of electromagnetic waves of wavelength between 100 μm (microwaves) and 10^5 m (long radio waves) within the troposphere.

Radio wave propagation and reception quality is determined by changes in the surface refractivity of air in the troposphere [3]. A change in the value of surface refractivity within the troposphere can make the path of a propagating radio wave to curve. The troposphere is the lowest layer of the atmosphere and it is the layer where most of weather events take place. It extends to an altitude of about 9 km near the poles, and 17 km at the equator. In the lower atmosphere, winds blow and clouds form resulting in rain and snow phenomena commonly called weather [6].

The ratio of the distance electromagnetic wave would travel in free space to the distance it actually travels in the earth's atmosphere is called the refractive index. The refractive index is symbolized by "n" and a typical value at the earth's surface would be 1.0003. The normal value of "n" for the atmosphere near the earth's surface varies between 1.00025 and 1.0004 [5]. Since the refractive index produces a number that is very close to unity, a scaled refractive index called refractivity is

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[1] Advanced Space Technology Application Laboratory, Obafemi Awolowo University, Ile – Ife, Nigeria
[2] Department of Physics, Obafemi Awolowo University, Ile – Ife, Nigeria
[3] National Space Research and Development Agency, Abuja, Nigeria
E-mail: ajileyeseun@rocketmail.com

used instead. Refractivity is symbolized by "N" and is a function of pressure, temperature, and vapour pressure. Refractivity near the earth's surface normally varies between 250 and 400 N-Units, the smaller the N-value, the faster the propagation. Refractivity values become smaller with decreasing pressure and decreasing moisture, but larger with decreasing temperature [16].

Empirical formulations for refractivity estimations are based on assumption that the atmosphere is homogenous and thereby dependent on relative humidity, pressure, and temperature profiles. However, recent data trends identify anthropogenic activities as major contributors to alterations in homogeneity of the atmosphere resulting in unusual climate variability. The increase in anthropogenic greenhouse gases, including carbon dioxide, have significant effects on gradual increase of global temperature thereby altering the balance of incoming and outgoing energy in the earth-atmosphere system. In view of the prevailing climate change and attendant global warming, spatial and temporal variations of surface refractivity are becoming of interest in climate and weather studies, and most especially to service providers in remote sensing and communication industries.

Previous studies carried out for some locations across West Africa on surface refractivity were based on extrapolated data from radiosonde measurements [4]. The results from radiosonde measurements lack the required resolution and coverage which is necessary for the investigations of spatial and temporal variations of surface refractivity across West Africa particularly in the lower atmosphere. These studies were limited to data from conventional meteorological stations and therefore were unable to resolve the spatial and temporal patterns emerging in the light of climate variations. Moreover, data gaps also exit while some of the stations have become defunct. The main focus of this study is the investigation of spatial and temporal variations of surface refractivity (N) and the implications for radio wave communication and climate variability. The data source is satellite based; it has wider coverage across West Africa and also longer measurement duration of over 22 years thereby making it more suitable for the study.

2.0 Equation for Calculating Surface Refractivity

The ITU Radio communication bureau, considered the necessity of using a single formula for calculation of the index of refraction of the atmosphere, the need for reference data on surface refractivity all over the world was also investigated. The necessity to have a mathematical method to express the statistical distribution of refractivity led to a recommendation that the atmospheric refractive index, n, be computed by means of the formula given by ITU-R (2003) and also applied by Adediji and Ajewole [2] as:

$$n = 1 + N \times 10^{-6} \qquad 2.1$$

where N is the surface refractivity expressed by

$$N = N_{dry} + N_{wet} = \frac{77.6}{T}\left(P + 4810\,\frac{e}{T}\right) \qquad 2.2$$

The dry term, N_{dry} of radio refractivity is given by

$$N_{dry} = 77.6\,\frac{P}{T} \qquad 2.3$$

The wet term, N_{wet} of surface refractivity is given by

$$N_{wet} = 3.732 \times 10^{5}\,\frac{e}{T^{2}} \qquad 2.4$$

P is atmospheric pressure (hPa), e is water vapour pressure (hPa), and T is absolute temperature (K). The expression in Eq. 2.2 may be used for all radio frequencies; for frequencies up to 100 GHz, the error is less than 0.5%. For representative profiles of temperature, pressure and water vapour pressure [14]. The dry term generally contributes about 70 % to the total value of the refractivity while the wet term contributes substantially to its variation. The dry term is proportional to the density and change in distribution of gas molecules in the atmosphere. The value of wet term of refractivity is due to the polar nature of water molecules [1].

The relationship between water vapour pressure *e* and relative humidity (RH) is given by

$$e = \frac{RHe_s}{100}\ (\text{hPa}) \qquad 2.5$$

with

$$e_s = a \exp\left(\frac{b\,t}{t + c}\right) \ \text{(hPa)} \qquad 2.6$$

where RH is relative humidity (%), t is temperature (°C), e_s is saturation vapour pressure (hPa) at the temperature t (°C) and the coefficient a, b, c are

a = 6.1121
b = 17.502
c = 240.97

and the values are valid for temperatures from -20 °C to +50 °C with an accuracy of ±0.20%.

Vapour pressure e can be obtained from the water vapour density ρ using

$$e = \frac{\rho\,T}{216.7} \ \text{(hPa)} \qquad 2.7$$

where ρ is given in g/cm³.

Ayantunji *et al.*, [4] studied the diurnal and seasonal variations of surface refractivity over Nigeria, using four years in-situ meteorological parameter data from eight stations over Nigeria. It was observed that the surface refractivity has higher values during the rainy season than during the dry season in all the locations. Adeyemi and Emmanuel [3] monitored tropospheric radio refractivity over Nigeria using Satellite Application Facility on Climate Monitoring (CM SAF) data derived from National Oceanic and Atmospheric Administration (NOAA) – 15, 16 and 18 satellites [11]. The results showed, among other things, that variations in each region and at different atmospheric levels were influenced by the north – south movement of the Inter-tropical discontinuity (ITD). This was supported by the results of Adediji and Ajewole, [2], which showed that the higher values of N during the rainy season were due to high air humidity due to the influence of Inter-tropical discontinuity zone (ITD) carrying high moisture laden air.

4.0 Climatic Zones across West Africa

The migration of Inter-Tropical Discontinuity (ITD) is fundamental to the understanding of West Africa climates. The ITD migrates northward and southward with the overhead sun reaching its maximum northward extent in July or August and its maximum southward extent in January. ITD is the boundary at the ground between the continental tropical air mass (cT) of northern origin and the maritime air mass (mT) of southern origin. The dry cT air to the north of the surface ITD overrides the mT air of southern origin, while the latter forms a wedge pointing north under the former. In December/January, the mean position of the ITD is at 5°N and this reflects general southward movement of wind and pressure systems at this time of the year. The southward migration is further assisted by the surface high pressure cells over the Sahara Desert, which is in turn related to the southward migration of the cyclones and anticyclones of the Mediterranean and northwest Europe [15].

In this work, the West Africa continental areas have been partitioned into four climatic zones (as shown in Table 1 and Figure 1): Zone 1 is Mangrove Rain Forest and is located below latitude 5°N; the zone is the most southerly zone with the characteristic of high annual rainfall; typically between 2,000 mm and 3,200 mm. Humidity is often high and rain is almost a daily phenomenon. Wide spread rainfall commonly last for five to six hours, but sometimes they persist all day. Skies are generally cloudy and overcast, but on most days, a few hours of sunshine may still be recorded. Day temperature could be between 24°C and 26°C; the nights are 3°C to 6°C cooler. The climatic zone is directly under the influence of coastal breeze from the Atlantic thereby keeping the moisture of the environment relatively higher than the rest of the climatic zones.

Zone 2 is Tropical Rain Forest and it is located within latitude 5°N and 10°N in West Africa. The climatic zone is marked by well-defined dry and wet seasons; November – March for dry season and April – October for wet season. The weather is humid and often accompanied with daytime conventional activity. Local thunderstorms and west-ward moving squall lines are prominent [13]. Rainfall occurs in heavy showers ranging between 1,000 mm and 2,500 mm. Some areas, such as Freetown, have considerably more rainfall with annual average of 3,000 mm. Rainfall regime is bimodal in pattern and separated by a short dry spell known as “August break” [13]. Temperatures reach their maximum of

33°C, although there is often a slight drop when rains are at their greatest.

Zone 3 is Guinea Savannah and it is located within latitude 10°N and 15°N in West Africa. Rainfall is not uniformly distributed, locations close to 15°N have monomodal regime while locations close to 10°N have bimodal regime [9]. The rainy period comprises of five months (April – August) and it ranges between 500 mm and 1, 500 mm per year. Temperature varies in the zone with daily average maximum of 32°C.

Zone 4 is Sudan Sahel and it is located within latitude 15°N and 20°N in West Africa. This zone receives very little rain in a year and it is classified as hot deserts with annual average temperature of 36°C (IPCC, 2007). Temperature in the zone shows a large diurnal variation with daytime maximum temperature of about 40°C and nighttime temperature of about 18°C [10]. The zone has monomodal rainfall regime. The annual rainfall is less than 250 mm thereby making it suitable only for some kind of adaptable plants to grow [8].

4.0 Source of Data and Processing Techniques

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 are satellite 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 [7].

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 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° and 20°N were used for the study.

Equation (2.6) was used to compute saturated vapor pressure, e_s. The e_s values were then substituted into equation (2.5) to obtain water vapor pressure, e. The values of e, P and T were then employed into equation (2.2) to obtain dry term and wet term of surface refractivity. Daily average of surface refractivity was obtained from summation of dry and wet terms for each station. The daily averages of surface refractivity were used to deduce the average dry and wet seasons; also monthly and annual averages were obtained. Mean values and standard deviations of the parameters calculated were also estimated in each climatic zone for a period of 22 years (1983 – 2005). Graphical and statistical analyses of the plots were carried out to be able to deduce the spatial and temporal variations of the parameters calculated.

5.0 Results and Discussion

Table 2 shows the seasonal variation of surface refractivity (N) estimated. In figures 2 and 3, the seasonal variation of surface refractivity at 2 m and 10 m heights for different climatic zones across West Africa were plotted. The results depicted the appropriate characteristic of rainfall regimes in climatic zones across West Africa. Occurrence of brief rainfall stoppage in climatic zones 1 and 2 in August was clearly shown in figure 2. The values of surface refractivity from satellite dataset have strong correlation with the previous results from ground meteorological stations. This is an indication of reliability in the use of satellite dataset for investigating seasonal variation of surface refractivity. The values of surface refractivity at 2 m were higher than that of 10 m in each climatic zone across West Africa because 2 m height has higher amount of moisture distribution than 10 m, and it is closer to the boundary layer – the source of evapotranspiration.

Since temperature and relative humidity decreased with height, surface refractivity results obtained at 2 m and 10 m indicated high level of measurement sensitivity to vertical profile of meteorological parameters at heights close to the earth surface. In zone 1, average temperature was 25^{o}C and 22^{o}C at 2 m and 10 m respectively; 27^{o}C at 2 m and 22^{o}C at 10 m in zone 2; 30^{o}C at 2 m and 26^{o}C at 10 m in zone 3; and 33^{o}C at 2 m and 31^{o}C at 10 m in zone 4. Average relative humidity at zone 1 was 95% at 2 m and 71% at 10 m, 82% at 2 m and 67% at 10 m in zone 2, 50% at 2 m and 33% at 10 m in zone 3, and 26% at 2 m and 14% at 10 m at zone 4. The spatial distribution and vertical profile of relative humidity and temperature across different climatic zones showed considerable variation; these are the factors responsible for the variability

Table 1: Selected WMO Stations across West Africa

S/N	Country	Location	Elevation (m)	Longitude	Latitude	WMO Index Number
CLIMATIC ZONE 1 (Mangrove Rain Forest) at Latitude < 5^{o}N						
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 5^{o}N - 10^{o}N						
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 10^{o}N – 15^{o}N						
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
CLIMATIC ZONE 4 (Sudan Sahel) at Latitude > 15^{o}N						
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

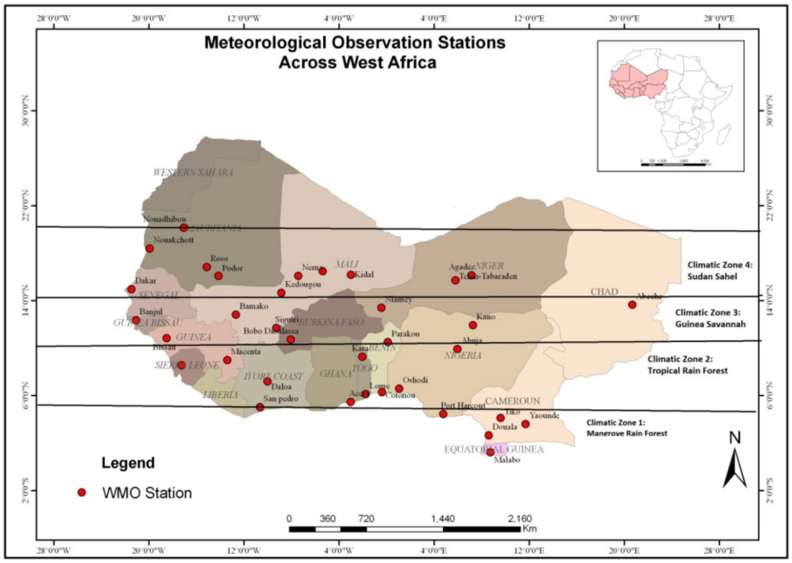

Figure 1: Map of West Africa showing the Study Location

Table 2: Seasonal Variation of Surface Refractivity Index (SRI) at 2 m and 10 m for different Climatic Zones across West Africa (1983 – 2005)

Month	SRI (N-Units) (2 m)				SRI (N-Units) (10 m)			
	Zone 1	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
Jan	300	261	273	270	265	262	261	265
Feb	318	287	285	271	268	266	259	260
Mar	323	291	291	272	268	266	258	258
Apr	324	298	313	281	269	270	261	256
May	320	297	328	311	269	270	266	257
Jun	307	287	323	325	269	270	269	262
Jul	303	282	322	329	268	270	269	263
Aug	303	277	319	326	268	270	269	264
Sep	307	283	321	325	269	270	269	263
Oct	309	284	310	288	269	270	265	258
Nov	311	284	298	276	269	269	262	259
Dec	310	281	279	270	269	268	259	261
Annual Average	**311±8**	**284±10**	**305±19**	**295±25**	**268±1**	**268±3**	**263±4**	**260±3**

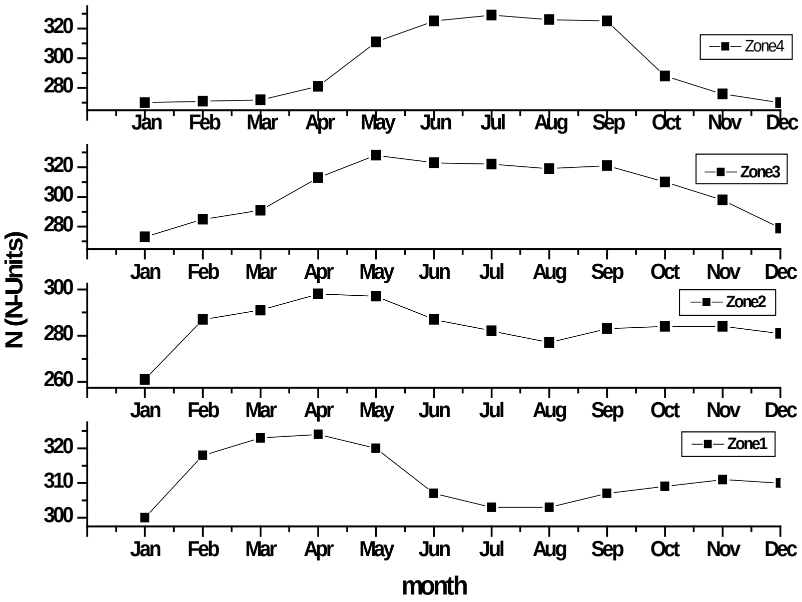

Figure 2: Seasonal Variation of Surface Refractivity Index (N) at 2 m for different Climatic Zones across West Africa (1983 – 2005)

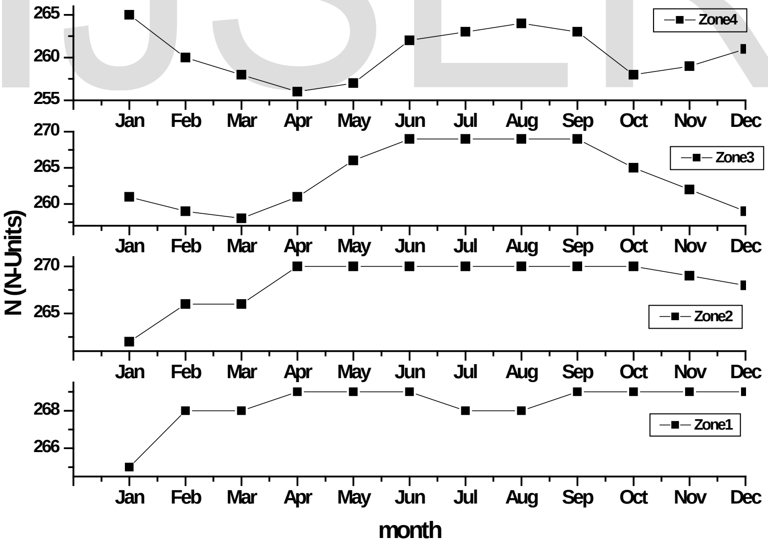

Figure 3: Seasonal Variation of Surface Refractivity Index (N) at 10 m for different Climatic Zones across West Africa (1983 – 2005)

of surface refractivity across West Africa. The values of relative humidity in each climatic zone were a reflection of rainfall patterns over West Africa from Latitude 3°N to 20°N.

The seasonal variation of surface refractivity at 2 m (1983 – 2005) in climatic zones 1 and 2 showed a similarity of bimodal pattern with maximum of 326 N-Units and 300 N-Units respectively in April. During this month, the humid maritime air mass has extended its influence up to 10°N resulting in heavy rainfall and slight decrease in temperature. The minimum values of 300 N-Units and 261 N-units were observed in January when the coverage of dry continental air is at the farthest southern location, covering the entire West Africa; humidity is very low, most especially in zone 2 where there is no influence of coastal breeze with characteristic high temperature.

In climatic zones 1 and 2, decrease in values of SRI showed dry weather characteristics in the month of August when the southwesterly air mass is at its farthest northern distance. During this month, surface refractivity was 302 N-Units and 277 N-Units in zones 1 and 2 respectively; this was brought about by short break in rainfall, low humidity, and cloud cover with slight decrease in daytime temperature. The seasonal variation of surface refractivity had general low values during the dry months and high values during the wet months due to increase in moisture and decrease in temperature distributions at the surface. Surface refractivity at 2 m in zone 1 were higher throughout the year when compared with zone 2; while the temperatures in zone 1 and 2 remain relative even, moisture distribution was boosted in zone 1 by longer rainy season and coastal influence in dry season.

Seasonal variations of surface refractivity in climatic zones 3 and 4 followed similar monomodal trend. Surface refractivity in climatic zones 3 and 4 were influenced by intensity of rainfall. Satellite observations showed that zone 4 has the least rainy season of about three months, while zone 3 has rainy season of about five months. In climatic zones 3 and 4, there was no occurrence of “August break”, surface refractivity showed that rainfall actually begins around June in the zones. This is because the effect of humid maritime air mass was not felt until later in the year. In the month of June, ITD movement is sufficiently beyond 15°N thereby causing rainfall in the southern side of ITD across West Africa. The maximum values recorded in zone 3 and 4 were 332 N-Units and 336 N-Units in June/July respectively while the minimum values of 272 N-Units and 269 N-Units were observed in December/January respectively.

In figure 3, the seasonal variation of surface refractivity at 10 m for different climatic zones across West Africa was plotted. Zones 1 and 2 had marginal seasonal range of 4 – 8 N-Units while zones 3 and 4 had seasonal range of 10 – 13 N-Units. The marginal range in seasonal variation at 10 m was caused by proximity factor to evaporation sources and moisture transport associated with both surface sensible heating and atmospheric latent heating. In zones 1 and 2, the minimum of 265 N-Units and 262 N-Units were observed in January while the maximum of 270 N-Units in May and 271 N-Units were observed in June in the zones.

The seasonal variation of surface refractivity across West Africa at 10 m was generally low in range when compared with variation at 2 m; the height closer to the surface is more highly moisturized by the warming and cooling effects of the ground in response to solar activities, which in turn forces changes in the boundary layer via transport processes brought about by mean wind, turbulence and waves. The least seasonal range was noticed in zones 1 and 2 and this is attributed to slight change in evapotranspiration due to cloud cover and coastal effect on moisture distribution.

The maximum values of 269 N-Units and 265 N-Units at 10 m in the month of July were observed in zones 3 and 4 while the minimum of 257 N-Units in March and 255 N-Units in April were noticed in zones 3 and 4. In zone 4, extremely low values of surface refractivity were observed in April and October. This is an indication that the zones experienced sudden decrease in humidity distribution and increase in temperature before and after the rainy season. From the plots, it was observed that dry months have low seasonal range in zones 3 and 4. This signals the strong influence and prevalence of dry continental air mass during the dry months. The decrease in surface refractivity is as a result of low moisture brought about by low humidity and high temperature.

6.0 Conclusion

Monthly variation of surface refractivity for different climatic zones across West Africa was estimated using satellite dataset spanning 22 years (1983 - 2005). Severity of climate dryness/wetness over West Africa was shown in the standard deviation of surface refractivity across the latitude. At 2 m, zone 4 had the highest standard deviation while zone 1 had the least deviation. The range of deviation was determined by seasonal moisture distribution. Seasonal variation of surface refractivity in climatic zones 1 and 2 showed similar trends of bimodal pattern and a deep in August due to short break in rainfall. The maximum of 326 N-Units and 300 N-Units were recorded in April while the minimum of 300 N-Units and 261 N-Units were recorded in January for zones 1 and 2 respectively. Surface refractivity values were generally low during the dry months and high during the wet months. Surface refractivity was observed to have higher values at 2 m than 10 m. Maximum values of 332 N-Units and 336 N-Units were recorded in June and July for climatic zones 3 and 4 while minimum of 272 N-Units and 269 N-Units were recorded in December and January respectively.

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