TROPOSPHERIC RADIO REFRACTIVITY OVER THREE RADIOSONDE STATIONS IN NIGERIA

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Abstract

The annual variations of radio refractivity parameter within the first 10 km of the troposphere are presented for three radiosonde stations in Nigeria, viz: Oshodi, a coastal area in the southwest, Minna, a middle belt Savannah region and Kano, a sub-Sahelian region to the north. Results have shown that the variations in each zone and at the different atmospheric levels are influenced by the north-south movement of the Inter-Tropical Discontinuity (ITD). Correlation coefficients between the combination of surface radio refractivity (N_s), and any of lower level refractivity (N_L), the upper level refractivity (N_U), and the total refractivity for the entire column (N_T), have been found to be more than 0.70.

Using an analysis of variance (ANOVA) technique on the upper air climatological data spanning over a decade, an empirical relationship of the form $N = \alpha(N_s)^b$ (α, b constants) has been established between refractivity aloft and its surface value, N_S, over the three stations in Nigeria. For instance, values of α and b for the refractivity parameters at Oshodi are 0.9308 and 0.9963 for N_L, 37.812 and 0.3547 for N_U, 3.1955 and 0.7820 for N_T respectively. Comparison made between the model and the actual values using the Kolmogorov Smirnov test have shown that the models for the three stations performed well during the dry season.

Keywords: Radio refractivity, troposphere, radiosonde stations, inter-tropical discontinuity, Savannah.

1. Introduction

The physical properties of the atmosphere determining the peculiarities of radiowave propagation are characterized by value of the radio refractive index. The radio refractive index of air, n, is slightly greater than unity, hence it is convenient to replace 'n' with the radio refractivity N defined by $N = (n-1) \times 10^6$. Thus the radio refractivity of air N is an important parameter considered in the propagation of radiowaves through the atmosphere. Its space-time variation results in scattering, sub refraction, super refraction, ducting, and absorption phenomena. The vertical profile simulations of the refractive index of the troposphere have gone a long way in providing useful explanations for the various radiowave propagation mechanisms (Batueva *et al.*, 1998).

Radiowaves with wavelengths shorter than about 10 m (Kolawole and Owonubi, 1982) are severely attenuated in the troposphere while waves with longer wavelengths can propagate through the troposphere with little attenuation. Therefore a radio engineer facing the task of designing a radio circuitry for the terrestrial broadcast has to give special consideration to the expected behaviour of the refractivity value along the propagation trajectory. Much more also, that the communication links operating at frequencies within the VHF up to microwaves depend much on the propagation conditions of the earth's troposphere, since the geometry of the path followed by the radio waves depends mostly on the vertical distribution of the atmospheric refractive index (Owolabi and Ajayi, 1979). Many of the oceanic coastal areas of the world are subject to land-sea circulation patterns that lead to spectacular refractive effects at both optical and radio frequencies. These effects often results from the contrast between the temperature and humidity at the sea surface and the temperature and humidity of the overlying air whose origin was over adjacent land areas (Richter, 1979). The refraction and ducting resulting form the air-sea contrast in refractive index has usually been discussed under the name 'evaporation duct'. Gossard (1978) gave a good account of the mechanism of generation of the evaporation duct, and some analytical approaches to its formation in the coastlines. Yasuo and Kenichi (1982) in their work on single mode condition of optical fibres highlighted that to calculate the cut off frequencies of the transverse electric field (TE_{01}), transverse magnetic field (TM_{01}) and transverse electromagnetic field (HE_{21}/TEM) modes which are important parameters in the designing of single mode fibres, the refractive index distribution in the core must be known.

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There is a general dearth of information on radio propagation measurements in the tropical countries of the world, therefore contributions based on the interpretation of few available data should play significant role in determining the propagation characteristics and hence, be of interest to the engineers involved in designing microwave radio links, terrestrial or satellite-based for the tropics. Bean and Thayer (1959) first investigated the correlation between the monthly means of surface refractivity N_S and the monthly means of the refractivity decrease in the first kilometre above the ground, ΔN. The expression relating both averages is given by:

$$-\Delta N = \alpha \exp(\beta . N_s) \qquad (1)$$

where α and β are constants that are characteristic for each region.

Pickard and Stetson (1950) established that a correlation existed between the transmission loss and the surface refractivity value, N_S. According to Lane (1961), this is only true when there is a good correlation between the refractivity decrease in the first kilometre ΔN and N_S. Studies by Kolawole (1983), Owonubi (1992), Babalola (1998) and Willoughby *et al.* (2002), have shown that N_S and ΔN are very well correlated in the African region.

In the study of refractive index turbulence, Wyngaard and Le Mone (1980), Fairall (1987) and Wyngaard *et al.* (2001) have observed that within the atmospheric boundary layer (ABL), the atmospheric refractive index fluctuates chaotically in time and in all three spatial directions. That near the top of the convective boundary layer, the values of the structure function parameters (which include temperature, water vapour and relative humidity) typically depart from those of the mixed layer forms and increase sharply to peak values before decreasing again at greater heights. Over Nigeria, the vertical structure of the atmospheric refractive index has been studied by Kolawole (1981) using radiosonde data from three stations. Willoughby *et al.* (1995) and Babalola (1996) studied the vertical gradient of refractivity in Nigeria predicting the frequency of occurrence of super-refraction and ducting at the different regions of the country. Batueva *et al.* (1998) and Zhamsuyeva and Zayakhanov (1998) have also studied the vertical distributions of this parameter in Russia. The objective of this paper is to study the space-time distribution of the monthly mean refractivity at different columns of the troposphere over three radiosonde stations in Nigeria with a view to establishing intra-layer relationship between surface, low-level and upper-level of this meteorological quantity. The results obtained were then subjected to the Kolmogorov-Smirnov (KS) test.

2. Data

The upper air data used in the computations reported in this paper were obtained from the archives of the Department of the Meteorological Services, Federal Ministry of Aviation at Oshodi in Lagos, Nigeria. The data obtained for the period 1975-1990 were those used in making the computations for the three stations as shown in Table 1.

Table 1: Geographic and Climatic characteristics of the stations

Station	Latitude	Longitude	Station Elevation (m)	Climate
Lagos/Oshodi	$6^0$28'N	3^0 28'E	19	Humid
Minna	9^0 37'N	$6^0$30'E	249	Partially humid
Kano	12^0 02'N	$8^0$30'E	480	Semi-arid

Table 2: Values of the best fit parameters α, and b in the regression equation of N_L on N_s, N_U on N_s, and N_T on N_s

Station	N	$N_L = \alpha (N_s)^b$					$N_U = \alpha (N_S)^b$					$N_T = \alpha (N_S)^b$				
		α	b	r	CV	p-value	α	b	r	CV	p-value	α	b	r	CV	p-value
Oshodi	12	0.93	0.99	0.77	59.5	0.003	37.81	0.355	0.57	32.2	0.050	3.20	0.78	0.73	53.4	0.007
Minna	12	5.15	0.71	0.99	99.9	0.000	179.2	0.093	0.99	99.6	0.001	24.8	0.43	0.99	99.9	0.000
Kano	12	6.28	0.68	0.99	99.9	0.000	170.0	0.104	0.92	83.1	0.000	23.9	0.44	0.99	98.9	0.000

2.1 Data analysis technique

The radio refractivity of air, N, for frequencies up to 100 GHz is generally expressed as

$$N = 77.6\frac{P}{T} + 3.75x10^5 \frac{e}{T^2} \qquad (2)$$

where P is the atmospheric pressure in hPa, T is the temperature in Kelvin and e is the vapour pressure in hPa (Bean, 1966; Adeyefa, 1995). The first term on the right hand side of Eq. 2 represents the dry component (N_{dry}) and the second term is the wet component (N_{wet}). While N_{dry} contributes about 66% of the total value of N, N_{wet} is mainly responsible for its variability.

The N_{dry} and N_{wet} term components from Eq. 2 are defined as

$$N_{dry} = 77.6\frac{P}{T} \; ; \quad N_{wet} = 3.75x10^5 \frac{e}{T^2} \qquad (3)$$

The analysis technique adopted here is identical to that in Aro (1975) where refractivity values were calculated for three layers: surface - 3 km, 3 - 10 km and surface - 10 km to be known as N_L (refractivity at the lower atmosphere), N_u (refractivity at the upper atmosphere and N_T (refractivity at the first 10 km of the atmosphere) respectively. N values at the surface and at each level were calculated using Eq.2. After this, we obtained for each station correlations of ($ln\ N_s$, $ln\ N_L$), ($ln\ N_s$, $ln\ N_U$) and ($ln\ N_s$, $ln\ N_T$). The correlation values for the above stated combinations i.e. between the surface refractivity and any of the columnar refractivity have been found to be more than 0.7 (see Table 2). An analysis of variance (ANOVA) table (not shown) was worked out for each station taking into consideration the associated F-ratios and the null hypothesis tests. This then suggests a regression relation of the form,

$$ln\ N = a + b\ ln\ N_s \qquad (4)$$

Hence, we obtain, from Eq. 4

$$N = \alpha\ (N_{ss})^b \qquad (5)$$

where $\alpha = e^a$. In Eqs. 4 and 5, N can be replaced by N_L, N_U, and N_T and the corresponding parameters α and b evaluated.

Next, N values at each level are calculated using the developed empirical relations. These were then examined using the KS test (Kendall and Stuart, 1979; Adedokun, 1989) in order to determine whether or not any agreement exists between the actual distribution function $F_N(x)$ and each model-generated series $F_C(x)$. As in Adedokun (1986), the maximum deviation between $F_N(x)$ and $F_C(x)$ is:

$$D_N = \max |F_N(x) - F_C(x)|$$

where x is ordered such that:

$$0 \le x_1 \le x_2 \le x_3 \;\ldots\ldots\ldots\ldots\ldots\ldots \le x_N$$

for N observations

If Ω is number of values $\le x$, $F_N(x) = \Omega/\sqrt{N}$

According to Kendall and Stuart (1979), critical values of D_N for 5 percent significant level is:

$$D_N(\alpha' = 0.05) = 1.3581/\sqrt{N}$$

Agreement exists between $F_N(x)$ and $F_C(x)$ if $D_N \le D_N$ (α' =0.05), for the significant level under consideration.

3. Results and Discussions

3.1. Mean Column Refractivity

Figs. 1, 2 and 3 show the monthly means of the columnar refractivity at the three stations, and its component parameters which include, the dry, N_{dry}, the wet, N_{wet} and the surface, N_S terms. Oshodi, (see Fig. 1a-c) being a coastal area, displays uniform and high values of all the columnar refractivity parameters. Here, surface (N_s) values are higher, all the year round, than those of lower (N_L) and upper columns (N_U) of the atmosphere. The refractivity values for the entire column N_T is constantly lower than those of the surface all the year round. N_s varies from about 350-400 N-units; N_L varies from about 330-350 N-units, N_u, about 300-310 N-units, and N_T, from about 320-350 N-units.

At Minna, an inland station (see Fig. 2a-c) N_S, N_L, N_U and N_T are closely related in values during the dry months of November to March; while during the rainy months of April to October, both N_L and N_T follow closely N_s and attain high values lasting between May and October. On the other hand N_U remained constant having values not quite different from its dry season values. The variations observed in N_L, N_T and N_S, during the rainy season, may be because the period is characterized by intense rainfall

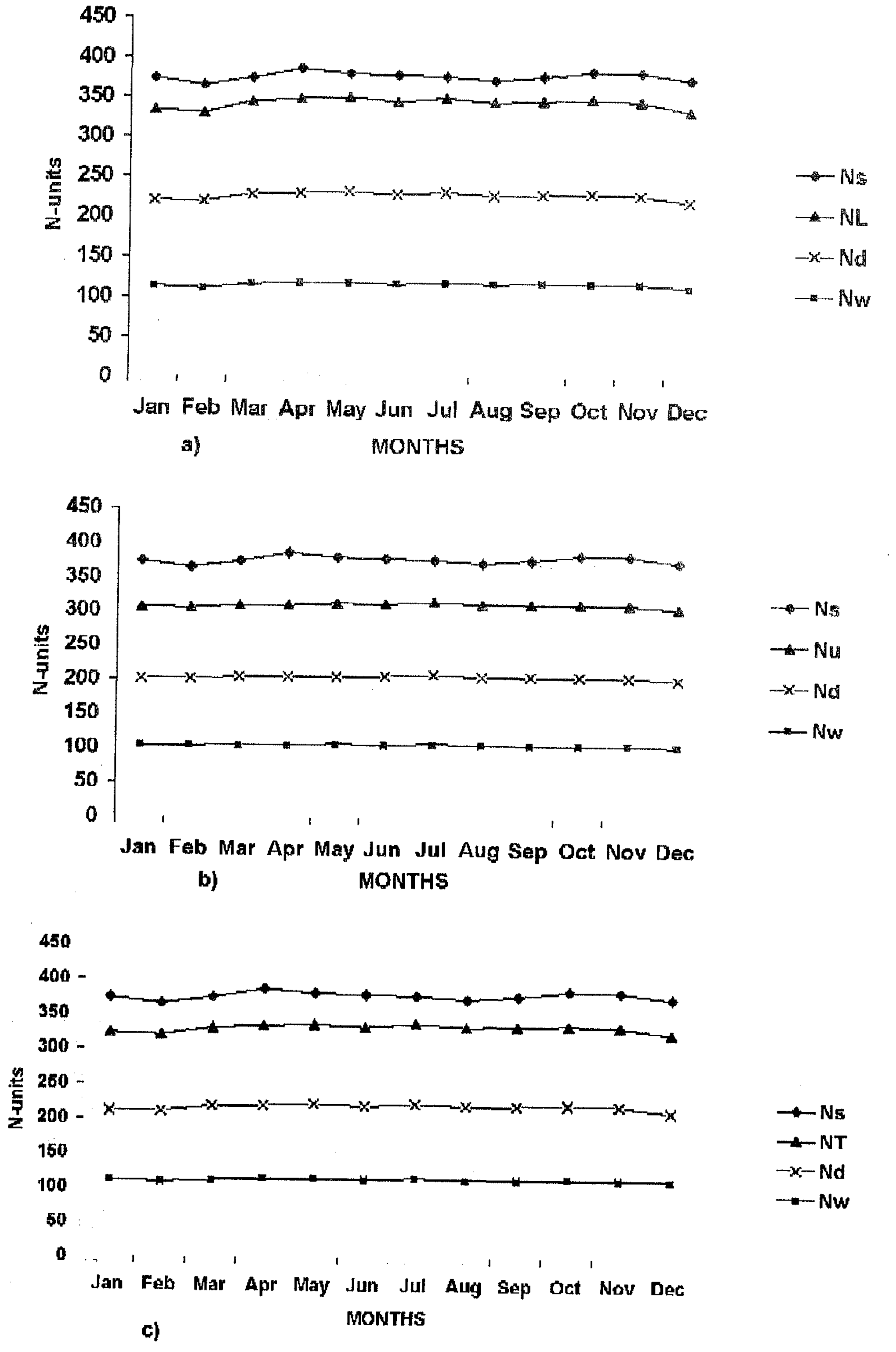

Fig. 1. Monthly variations of mean refractivity at different atmospheric levels and related parameters at Oshodi.

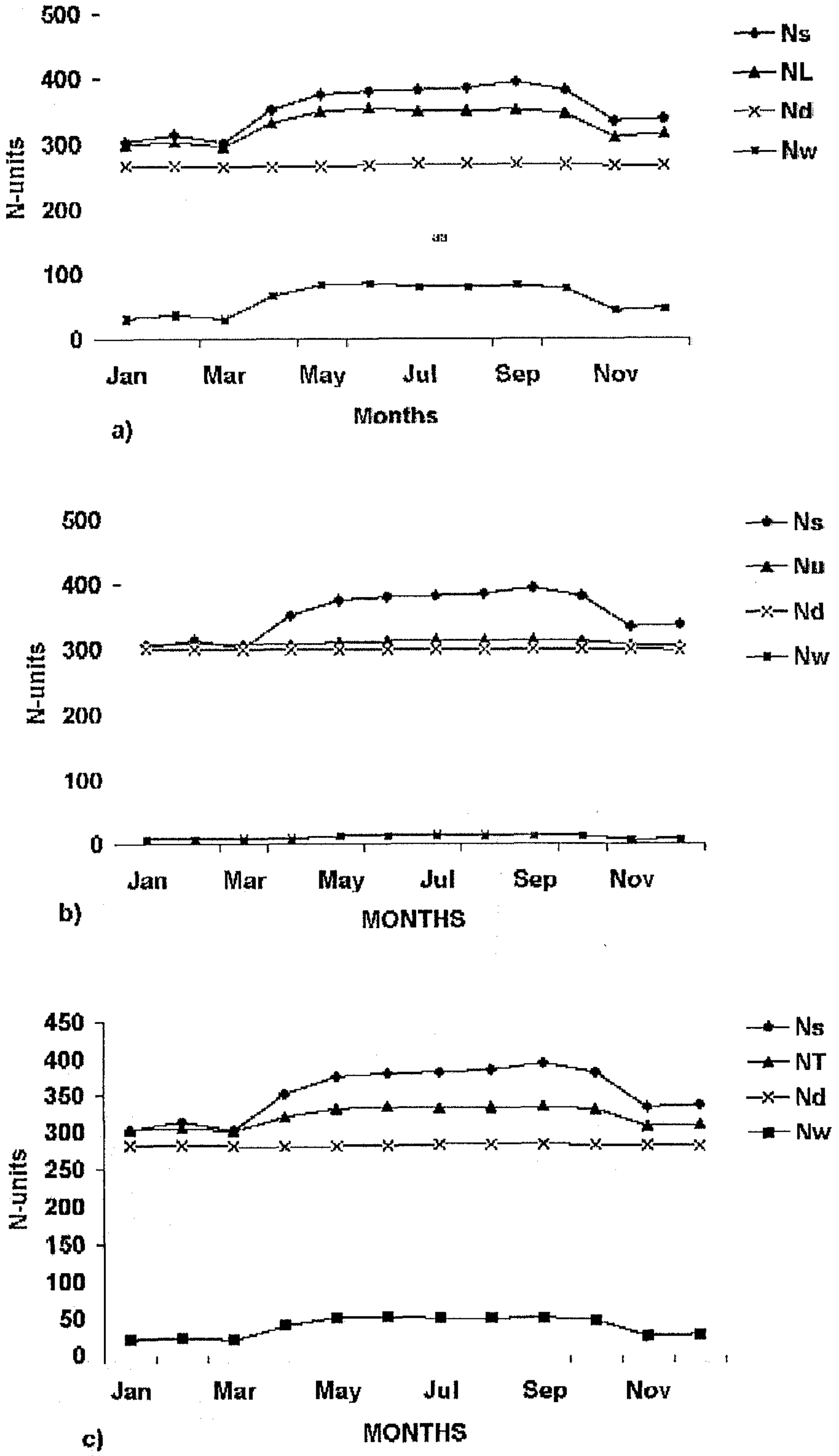

Fig. 2. Monthly variations of mean refractivity at different atmospheric levels and related parameters at Minna.

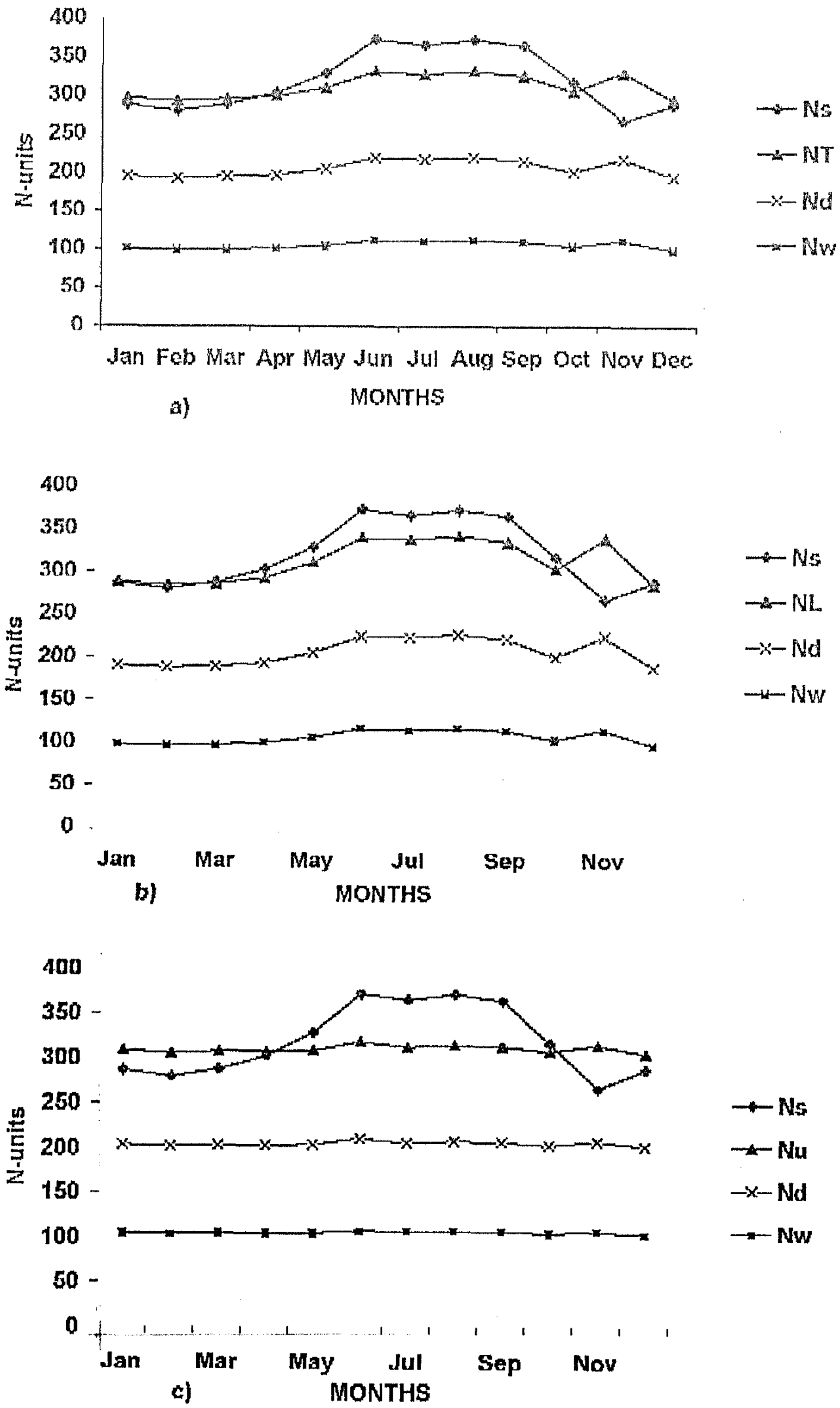

Fig. 3. Monthly variations of mean refractivity at different atmospheric levels and related parameters at Kano.

which keeps the atmosphere in constant supply of water vapour. The refractivity at the upper level, (N_U), is not as high as N_L and N_T in this station during the rainy period. This may be attributed to the fact that in the higher layers, perpetual accumulation of water vapour is prevented by cloud formation and prevailing winds. Hence low values of N results (Aro, 1975).

At Kano, a sub-sahellian station, (see Fig. 3a-c), N_L, N_U and N_T display similar seasonal pattern. During the dry months of November to April, their values compare well with that of N_S, whereas during the rainy months, N_U displays higher values than them all. N_U values here also are uniform throughout the year. All except N_U, display higher values during the rainy season than the dry season period. This shows the dependency of refractivity on water vapour.

At all the stations, and for all the atmospheric levels, the dry (N_{dry}) term is the dominant contributor to refractivity while the wet (N_{wet}) term is responsible for the variations observed in refractivity. This is in conformity with the result obtained by Adeyemi (1992), Adeyefa (1995) and Willoughby *et al.* (2002) where in each case it was highlighted that the dry term (N_{dry}) contributes about 60-70% to refractivity irrespective of the season.

Table 2 shows the best fit parameters α, b obtained for each station, the coefficient of variation (CV) and the probability p-value at which the null hypothesis was either accepted or rejected. Observing Table 2, a high degree of relationship exists between N_L and N_S (see Table 2a), N_U and N_S (see Table 2b), N_T and N_s (see Table 2c). The null hypothesis is rejected at $p < 0.05$ for all the cases. Hence for all, null hypothesis is hereby rejected. The coefficient of variation is higher in the midland and Northern zone than in the coastal (Southern) zone of Oshodi, suggesting a higher amount of variation in the more arid zone as is normally expected (Adedokun, 1983). This may be due to strong atmospheric turbidity experienced in the North (McTainsh, 1984). The generally high correlation coefficients in Table 2 are normally typical of monthly mean data (Reitan, 1963). However, this degree of correlation decreases for shorter time (e.g. daily/hourly) data (Bolsenga, 1965).

To verify the reliability of the relations obtained in Table 2 above, we feed in N_S (mean of monthly) values obtained for the months of November-March, depicting the dry season period, for the individual stations, to the regression relations. The results are shown in Table 3.

Comparing the actual and calculated values at both season and at different stations as shown in Table 3, the agreements between them is remarkable. As can be observed in the table, Kano, a sub-sahelian station, was well monitored at the three atmospheric levels considered by the models, because the residuals are low. Refractivity at the three levels were fairly well monitored at Oshodi (residuals are fairly high). At Minna, a midland station, the low level refractivity N_L was well monitored (low residuals), the upper level, fairly well monitored (fairly high residuals), and N_T (refractivity for the total column was badly monitored by the model during the rainy season of April to October (residuals are high). During the dry season, N_T, at Minna, was fairly well monitored by the proposed model. The observation at Minna which showed least agreement at the upper level during the rainy season may be because of its nearness to ITD (Adedokun, 1983) for that time of the year. Also, Minna, being closer to Niger River, might experience local variability with high water vapour aloft than expected from low level observations. The low agreement observed in Oshodi could be because Lagos is a coastal station.

3.2 The Kolmogorov-Smirnov (KS) test:

As have been defined earlier, the KS test is used to determine whether agreement exists between the actual and the calculated values. Applying this test to the low-level, N_L upper-level N_U and total refractivity for the column N_T, the following results were obtained as shown in Table 4.

Table 4 indicates that the model formulated for refractivity at low level, N_L refractivity at upper level, N_U and total refractivity for the column N_T performed well only in Kano. At Oshodi and Minna, none of the models performed well. Oshodi is a coastal station, hence oceanic (sea-breeze) effects may be responsible for this situation. Minna on the other hand is a midland station, but this station is located on the wet terrain of the river Niger. Therefore, sea-breeze effect may also be responsible for its own situation too.

For effective monitoring of the seasonal changes, we have looked closely at the performance of the models over each of the stations during the dry season (November-March) and the rainy season (April-October), as shown in Table 5.

Performance of the Models during the Dry Season:

(i) The individual model for N_L (refractivity at the lower level of the atmosphere) for the different stations, performed well at the stations.

(ii) The individual model for N_U (refractivity at the upper atmosphere), for the different stations performed well at all the stations.

Table 3: Application of the proposed model for each of the stations.

(a) Station	Equations: $N_L = 0.9308\ N_S^{0.9963}$; $N_U = 37.812\ N_S^{0.3547}$; $N_T = 3.1955\ N_S^{0.782}$							
Oshodi	N	N_S	N_L		N_U		N_T	
			actual	calculated	actual	calculated	actual	calculated
Dry season	5	374	338	340.6	308	309.2	326	328.5
Rainy season	7	380	348	345.6	312.	310.8	334	332.3

(b) Station	Equations	$N_L = 5.149\ N_S^{0.7089}$; $N_U = 179.2N_S^{0.0932}$ N_T 24.821; $N_S^{0.4361}$						
Minna	N	N_S	N_L		N_U		N_T	
			actual	calculated	actual	calculated	actual	calculated
Dry season	5	381.7	304.2	306.5	306.3	306.7	305.1	306.6
Rainy Season	7	378.2	346.8	346.0	311.7	311.6	330.9	330.3

(c) Station	Equations	$N_L = 6.276\ N_S^{0.6746}$; $N_U = 169.96\ N_S^{0.1043}$; $N_T = 23.934\ N_S^{0.4433}$						
Kano	N	N_S	N_L		N_U		N_T	
			actual	calculated	actual	calculated	actual	calculated
Dry season	5	302	297	295.6	309	308.3	302	300.9
Rainy Season	7	346	323	324.0	312.	312.7	316	319.6

Table 4: Results of KS test on actual and model N_L, N_U and N_T values.

Stations		N_L	N_U	N_T
	D_N (α=0.05)	D_N	D_N	D_N
Oshodi	0.392	0.559	0.411	0.538
Minna	0.392	0.584	1.888	1.873
Kano	0.392	0.343*	0.347*	0.211*

* Association exists between actual values and model values at 5 percent significant level.

Table 5: Results of the KS test on actual and model during the dry and the rainy seasons

Stations	D_N (α=0.05)	Values of D_N for various refractivity parameters during the dry season.			D_N (α=0.05)	Values of D_N for various refractivity parameters during the rainy season		
		D_N for N_L	D_N for N_U	D_N for N_T		D_N for N_L	D_N for N_U	D_N for N_T
Oshodi	0.607	0.548*	0.266*	0.458*	0.513	0.559	0.411*	0.538
Minna	0.607	0.583*	1.360*	1.808*	0.513	0.513*	1.888	1.873
Kano	0.607	0.343*	0.192*	0.142*	0.513	0.271*	0.317*	0.241*

* Association exists between actual and model values at 5% significant levels.

(iii) The models for N_T performed well at two of the stations, which are Oshodi and Kano.

These show that the models performed well during the dry season at all the stations except Minna, where the N_T model could not satisfy it. From Table 3, it could be observed that, during this period of the year, overestimation of refractivity parameters persists in two of the stations, which are Oshodi and Minna whereas at Kano underestimation occurred. The observations at Oshodi and Minna could be likened to the influence of sea breeze from the ocean and from Niger River respectively. This gives the surface additional moistening giving rise to larger values of atmospheric water vapour than observed. Whereas at Kano, a sub-Sahelian station, the region is covered during the dry season by the Saharan dust plume (Kalu, 1979) where the maximum concentration occurs at about 1000 m (900 mbar). Adsorption of water vapour by the dust particulate matter and abnormal daily variation in dew point temperatures typify the dry season. Therefore, humidity at surface may not well represent the humidity aloft. This results in underestimation of the refractivity parameters at this station during this period.

Performance of the Models during the Rainy Season

(i) Models for N_L performed well at Minna and Kano alone.

(ii) Models for N_U performed well at Oshodi and Kano but not at Minna.

(iii) Models for N_T performed well only at Kano. Those for Oshodi and Minna do not perform well.

In general, only Kano record good performances of the models for the various parameters during the rainy season.

The models for Oshodi and Minna tend to underestimate the refractivity parameters during this period, while those of Kano tend to overestimate them (see Table 3). The observations at Oshodi and Minna could be likened to the occurrence of the little dry season (LDS) accounting for the existence of lower water vapour parameter at the surface. Whereas at Kano, the position of the ITD which reaches up to 22-25^{0}N in August (Adejokun, 1966; Adedokun 1978) may account for the overestimation observed in the refractivity parameters.

4. Conclusion

At Oshodi, a coastal station, higher and uniform values of refractivity parameters are observed throughout the year (see Fig. 1). Mean values of N_S ranges between 350 and 400 *N*-units, N_L, between 330 and 350 *N*-units, N_U, between 300 and 310 *N*-units and N_T, between 320 and 350 *N*-units. In the case of Minna and Kano, refractivity parameter values during the dry season are quite lower than those of rainy seasons. In other words, in these stations, lowest values are found in the dry season period. The difference observed between the Southern and the Northern stations in refractivity values may be likened to the fact that the precipitation climatologies of both region differs appreciably (Balogun, 1981; Garbutt *et al.*, 1981).

Using the analysis of variance (ANOVA) technique, a relation of the form

$$N_L = \alpha N_S^b \quad (\alpha, b \text{ are constants})$$
$$N_U = \alpha N_S^b$$
$$N_T = \alpha N_S^b$$

connecting refractivity at lower level of the atmosphere, (N_L) upper level of the atmosphere, (N_U) and total refractivity in the first 10 km column (N_T) with surface refractivity (N_S) have been established from upper air climatological data observed over Nigeria (see Table 2). These models when used to evaluate, on a monthly basis, refractivity parameter at each atmospheric level yielded an encouraging results in spite of the known physical draw backs inherent in efforts to infer water vapour aloft using surface conditions (Reber and Swope, 1972).

As demonstrated, using Kolmogorov-Smirnov test on the monthly evaluation of the refractivity parameters, the models for the three refractivity columnar parameters performed well at all the stations during the dry season while during the rainy season, only Kano has good record of performance for all parameters, Oshodi has good record only for N_U model and Minna has good record for only N_L model. This shows that that the models developed for Kano at all levels performed better in the two seasons in Nigeria than those of Oshodi and Minna. This may be because the fluctuations of the inter-tropical discontinuity (ITD) have high influence on the atmosphere at Kano than at Oshodi and Minna. Oshodi, a coastal station, and Minna, a station located on the wet terrain of Niger River, are mainly under the influence of water-air interaction mechanisms which are still subject of investigation.

Finally, the poor agreement observed at Oshodi and Minna therefore may be due to the fact that some atmospheric parameters which have high influence on the circulation aloft in the stations were not incorporated into the analysis. A multivariate regressional model which will take care of these would be considered in future along with more case studies.

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