INVESTIGATION OF POWER LAW WIND EXPONENT WITHIN THE LOWER BOUNDARY LAYER AT ILE-IFE, NIGERIA.

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ABSTRACT

A sound detection and ranging (SODAR) equipment installed on the roof of a two-storey building at the Department of Physics, Obafemi Awolowo University Ile-Ife, Nigeria (7.52° N and 4.52° E), 294 m height above mean sea level and about 20 m above the ground level has been used to study on continuous basis the planetary boundary layer (PBL) wind. Eighteen thousand (18000) sets of hourly averaged data for the wind speed from 30 m above the surface to 500 m height at 20 m intervals had been used to study the power law wind exponent over Ile-Ife Nigeria. The data covered about two and half years (from June 2009 to December 2011). Exponent was found to increase with height and decrease with surface wind speed. It was also discovered that had both diurnal and seasonal variations. The values at daytime were lower than at nighttime and the wet months had higher values than the dry months. Its average for the dry months was 0.33 while the average for the wet months was 0.45.

INTRODUCTION

Boundary layer winds had been studied in time past for various reasons ranging from the study of weather system dynamics to wind energy applications. In the design of tall buildings, civil engineers need information about the vertical wind structure around the building and the maximum wind speed the building needs to withstand. The nature of the vertical wind profile also dictates the structure of buildings, bridges, pollutant dispersion and wind turbines among others (Stull, 1988).

In most weather stations in Nigeria, wind speed are observed at 10 m height or below, whereas in studying the suitability of wind energy generation in the country, information about wind speed is needed at the hub height which is usually some height greater than 10 m. Hence there must be a way of extrapolating the wind speed at the hub height from the available 10 m wind.

Wind speed profiles within the boundary layer are generally represented by two relationships; the logarithmic and power law profiles. While the logarithmic wind profile finds its application within the lowest 100 m above the surface, the power law wind profile is valid within the lowest 600 m above the ground. Hence for most meteorological purposes and engineering applications, the power law wind profile is used (Linsley *et al.,* 1988).

The wind field in the boundary layer is largely controlled by frictional drag imposed on the flow by the underlying rigid surface. The drag retards air motion that is close to the ground and gives rise to a sharp decrease of mean horizontal wind speed as the surface is approached. In the absence of strong thermal effects, the depth of this frictional influence depends on the roughness of the surface. The wind therefore increases with height in the boundary layer.

Ile-Ife, Nigeria, is located within the tropics. Here, there are two prominent seasons, namely; dry and wet seasons. The meridional movement of the Inter-tropical discontinuity (ITD) dictates the two seasons. ITD is the meeting point over land of moist southwesterly stream from the ocean and the dust-laden dry northeasterly trade wind from the Saharan desert, while the meeting point over the ocean is called the Inter-Tropical Convergence Zone (ITCZ) (Balogun, 1980).

The position of the ITD on surface chart usually coincides with the position of a low-pressure system also known as a heat low. The characteristic behaviour of the ITD is such that any station north of it experiences cold dry dust-laden winds locally known as 'Harmattan' in West Africa, while any station south of it is brought under the influence of warm south westerlies, which brings about convective cloud formation leading to thunderstorm and rain, depending on the position of the station relative to the ITD (Adedokun, 1978). Previous studies revealed that the ITD

migrates between 4° N and 25° N during the course of a year (Hamilton and Archbold 1945).
The intersection on the surface migrates with the solar cycle attaining its most northerly position between latitudes 22-25° in August. As a result, the monsoon winds penetrate far into the West/North Africa hinterland covering the whole of Nigeria during this period, bringing moisture and rain into the Sahel and South Sahara. Between late August and early September, the ITD line starts to recede southwards till it reaches the most southerly position about latitudes 4-6° N (in January). During this time, the north easterly winds, (locally known as Harmattan) dominates over the region, bringing dust as far as south of West African coasts (Adedokun, 1978). Balogun (1980) further affirmed that as southwest moist air becomes thicker over West Africa. The thicker layer clouds cut off insolation and consequently reduce convection development and thunderstorm activity (the august break phenomena). Generally, the region under study is characterized by low winds. It is therefore important to investigate the suitability of wind energy generation vis-à-vis the power law wind exponent.

THEORY AND METHODOLOGY

Theory

According to Johnson (1959) and Geiger (1965), the power-law is represented as;

$$\frac{U}{U_0} = \left(\frac{Z}{Z_0}\right)$$

Where U is the wind speed at height Z, U_0 is the wind speed at a reference height Z_0 usually 10 m.
is an exponent which varies with surface roughness, surface stability and surface wind speed. According to Alvi and Abdalla (1990), the value of varies between 0.1 and 0.6, while other researchers maintained that the value varies between 0.1 and 0.4 (e.g. Jarass, 1981). From existing records, it was estimated that for coastal areas, exponent takes the value of 0.15, while in inland locations, the parameter is higher and takes the value of 0.3 (Pashardes and Christofides, 1995).

This power law wind exponent is investigated in this work to ascertain whether the value at Ile-Ife agrees with what obtains in the mid-latitudes as found in the literature.

Experimental Set-up

The instrument used for this study is a METEK PCS.2000/24 acoustic sounder (sodar) system which uses a phased array antenna consisting of 24 loudspeakers of 1000W maximum output power, serving as transmitters as well as receivers. In order to reduce an interference with environmental noise and to suppress the influence of echoes from fixed targets, the acoustic antenna is lined with an absorbing material. The speakers are switched to 4 different phases (0°, 90°, 180° and 270°) to direct the beam to one of the 5 directions; the fifth direction is vertically upward (METEK, 2006).

In the present operation, the PCS.2000/24 sodar system was configured to give return values of the wind speed and direction from 30 m to about 830 m (topmost measurement height was 830 m). A vertical spacing of 20 m was selected between successive measurement levels. In 2010, the sodar system was configured to include surface data. For this reason the 2010 data had wind speed values at height 10 m. While for other periods, the lowest measurement height was 30 m. In order to be free of obstruction, the sodar antenna (Figure 1) was installed on the roof of a two-storey building at the Department of Physics, Obafemi Awolowo University Ile-Ife, Nigeria with coordinates 7.52° N and 4.52° E and 294 m height above mean sea level and about 20 m above the ground level. The system was connected to an indoor desktop computer (Figure 2; a UPS was provided to solve the problem of power outage that was not more than two hours) which was controlled by proprietary software provided by the instrument manufacturer. Subsequently, the wind profiles were then stored as 10 minutes averages.

The system was installed in June 2009 and had been in operation since then, for the monitoring of wind profiles in the boundary layer.

Fig. 1: Metek Sodar Antenna Installed at the Roof Top of Physics Building, Obafemi Awolowo University, Ile-Ife

Fig.2: The Indoor Desktop Computer that Controls the Sodar Antenna with the UPS; the Monitor Displays the 10 Minutes Averages of Wind Profile Measured by the System, the Gaps Indicates Periods of Power Outage.

Data Processing and Analysis

As a way of data quality control provided within the METEK software (METEK graphics), wind speed values above 30 m/s were screened out without replacement from the data set (30 m/s being the upper limit of valid wind speed value measurable by this model of the METEK sodar). The obtained data were then subjected to data reduction by means of locally developed software using the AutoIt Vs.3 language. This reduced the 10 minutes averages to daily hourly averages.

The data used for this investigation comprised of about 18,000 data points of daily hourly averages starting from June 2009 to November 2011 with the exemption of November and December 2009, January 2010 and March 2011 when the equipment was not functional or that there was a prolonged electric power outage. The wind shear exponent was investigated in this study to see how it varies with height, month of the year, surface wind speed and time of day. Wind speed profile was also studied under different stability condition for the area under study.

RESULTS

Variation of Power Law Wind Exponent With Height

Figure 3 presents the variation of power law wind exponent with height when the wind speeds are averaged over all the period and all the hours. The values of corresponding to Z_0 values of 30 and 50 m were computed from the whole data sets while values corresponding to Z_0 value of 10 m are based on only 2010 data (about 8,000 data points). It is generally observed that values increase with height, this is in contradiction to what was reported by Alvi and Abdalla (1990) when they studied the wind speed profile over Bahrain, a desert region in the Middle East, they reported a decrease of with height. This contradiction may be attributed to the location and the canopy level where the experiment was conducted. However, that the values tend towards a constant at about 500 m height is in consort with what the authors reported.

This implied that extrapolating the wind at a particular height from the surface is dependent on the height at which extrapolation is done, the exponent is applicable to the height below 500 m. However, above 500 m, a constant value can be used such that an increase in value with Z_0 is also observed from Figure 3. A significant increase is observable above 150 m height.

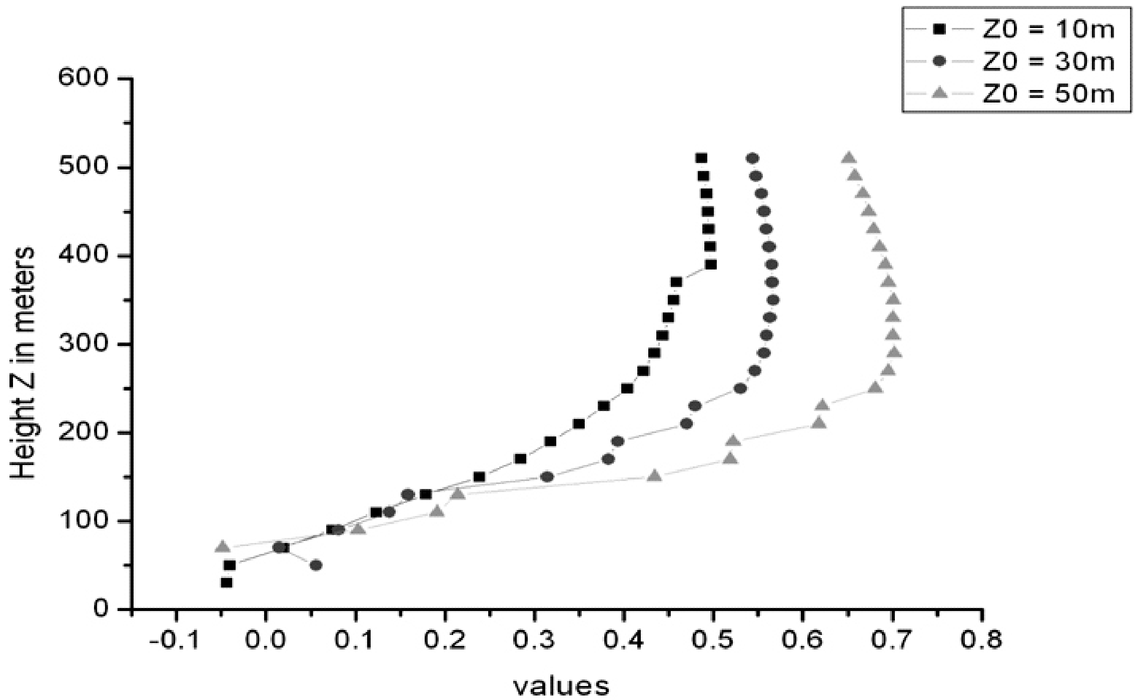

Fig 3: Variation of Power Law Wind Exponent with Height for Different Values of Z_0

Variation of With Surface Winds

Figure 4a presents the variation of the power law wind exponent with surface winds i.e. wind at 10 m when Z_0 is taken to be 10 m. The data used for this plot were that of the daily hourly averages for the year 2010 alone corresponding to about 8,000 data points but further reduced into monthly hourly averages. It can be observed that has an inverse relationship with the surface wind speed, that is, it decreases with increasing surface wind speed in consistence with the observation of Alvi and Abdalla (1990). Figure 4b is the same as Figure 4a except that Z_0 is 30 m. It also established the fact that decreases with increasing 30 m height wind speed.

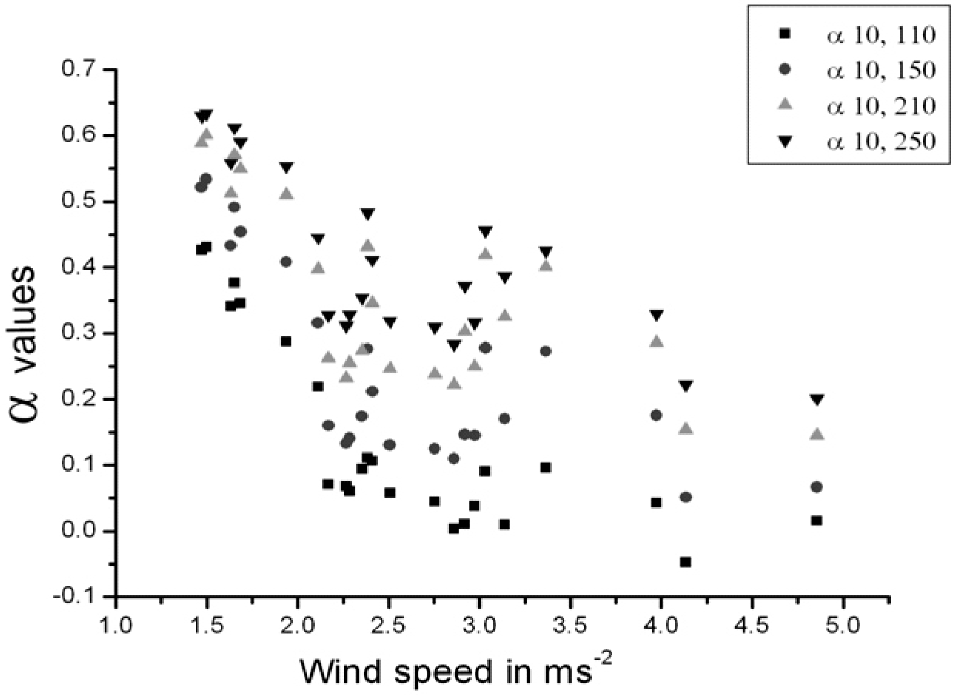

Fig. 4a: Variation of with Surface Wind Speed (Wind at 10 m)

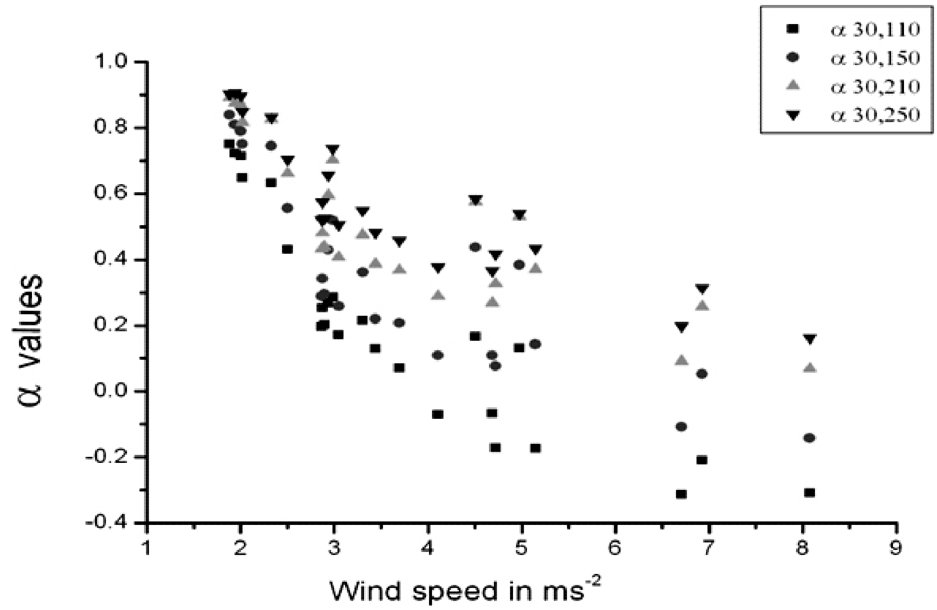

Fig. 4b: Variation of with Wind Speed at 30 m

Effects of Different Stability Conditions on Exponent

The values of exponent , calculated for different stability conditions are presented in Table 1. Figure 5 presents values for different times of the day corresponding to different stability conditions. Two segments are obvious from the Figure; the first segment corresponds to when Z_0 is 30 m and the second segment corresponds to Z_0 = 10 m. When the atmosphere is transiting from unstable condition to stable condition, the surface layer first becomes stable and decouples from the upper layer. For this reason, the atmosphere may be stable at height 10 m and may not be stable at 30 m height and above. This is the major reason why there is difference between the shapes of the two segments in Figure 5.

For the first segment, values corresponding to Z_0= 30 m show a unilateral increase from predawn to evening. This is a bit different from what was observed from the second segment where Z_0= 10 m. The newly established unstable conditions (Morning and afternoon) are associated with low values of , while stable conditions (evening and predawn) are associated with relatively higher values of . Thus, values are expected to be higher during nighttime than during the day. This is because turbulent mixing is expected to weaken the wind shear during the day due to high insolation, this effect is absent during the nighttime giving rise to strong wind shear and higher value. Because the shape of the second segment agrees with established facts from literature more than the first segment, therefore, the wind at 10 m is more realistic to use as initial wind value for extrapolating upper level winds using the power law relationship.

Table 1: Values During Different Stability Conditions

	Stable	**Neutral**	**Unstable**		**Neutral**	**Stable**
	Predawn (12 - 6 am)	Dawn (6 -7 am)	Morning (7 - 12 am)	Afternoon (12 - 5 pm)	Dusk (5 -6 pm)	Evening (5 - 12 midnight)
30,100	-0.04	-0.17	0.06	0.25	0.17	0.60
30,150	0.14	0.14	0.19	0.40	0.44	0.72
30,210	0.3	0.37	0.37	0.56	0.58	0.80
30,250	0.38	0.43	0.46	0.62	0.59	0.82
10,110	0.17	0.04	0.03	0.09	0.11	0.27
10,150	0.26	0.18	0.14	0.17	0.28	0.41
10,210	0.34	0.29	0.27	0.28	0.43	0.51
10,250	0.40	0.33	0.33	0.35	0.48	0.55

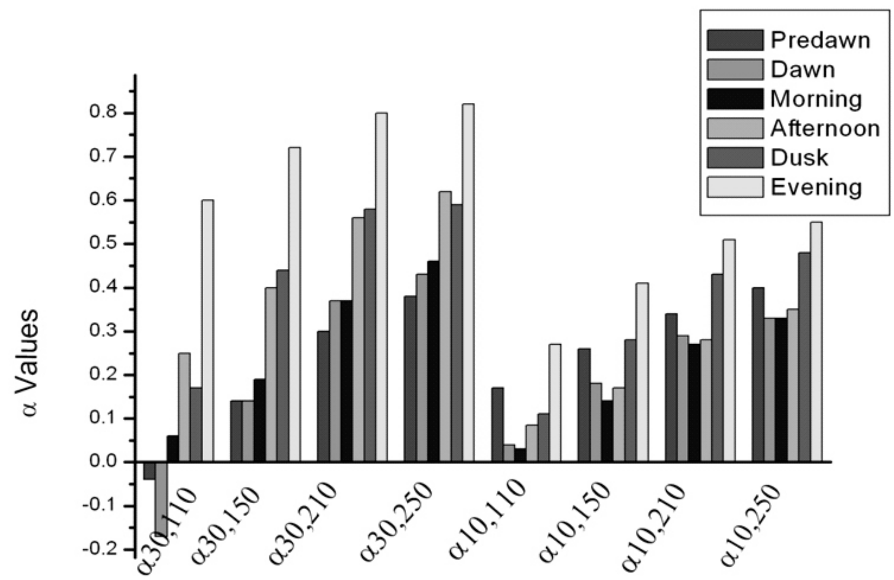

Fig. 5: Values for Different Stability Conditions

Diurnal Variation of

The diurnal variation of is presented in Figure 6. It is observed that the values of are relatively higher during the night time periods than during the day. Two minima are noticeable; one is between 0400 0500 hrs and the other between 1800 and 1900 hr. (01hr refers to average of 10 minutes measurements taken between 0100 and 0150) with the one around 0400 hr being more pronounced. The low values of during the day are expected as convection tends to weaken vertical wind shear during the day.

When Figure 6 is compared with Figure 7, the reason for the deep at about 0400 hr is obvious. It has been established earlier in Figure 4 that wind shear parameter decreases with increasing surface wind speed. Figure 7 shows an increased surface wind speed at 0400 hr. A careful look at the data set prior to averaging reveals a wind speed maximum between the hours of 04hr and 05hr, this is what Figure 7 reveals at 04hr. It had also been established by Akinlade and Ayoola (2012) that the diurnal wind pattern over the station reveal two maxima; one between 04 and 05 hrs and the other between 20 and 21 hrs. It is this increase in wind speed values at predawn that is responsible for the characteristic different wind profile observed at 04 hr in Figure 7 and also resulted in the deep noticed at 04 hr in Figure 6. Apart from this unique behaviour of the wind profile at 04hr below 120 m, the vertical wind profiles are in agreement with what is obtained in the literature except that there seems to be little or no disparity between night time and day time situations when the data are averaged over the entire period.

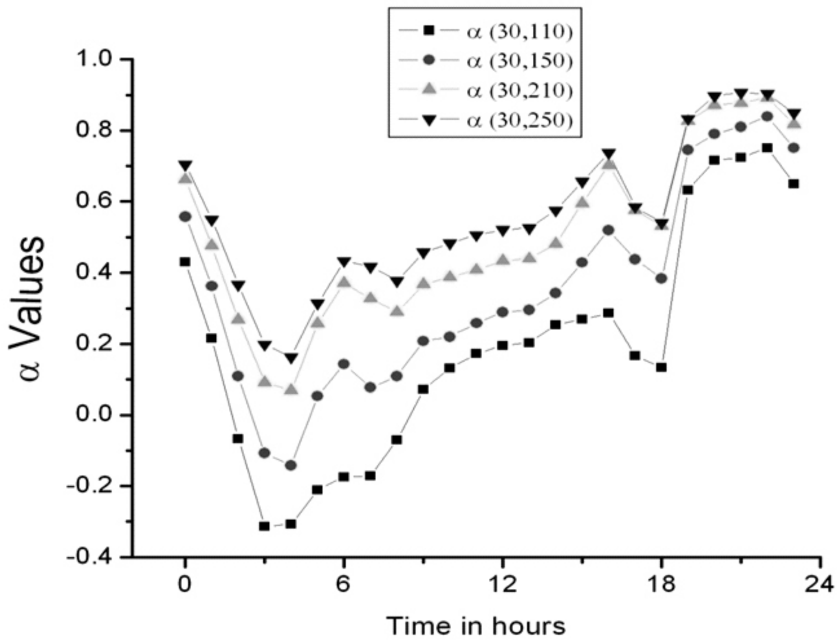

Fig.6a: Diurnal Variation of for Different Step Changes when Z_0 = 30 m (whole data)

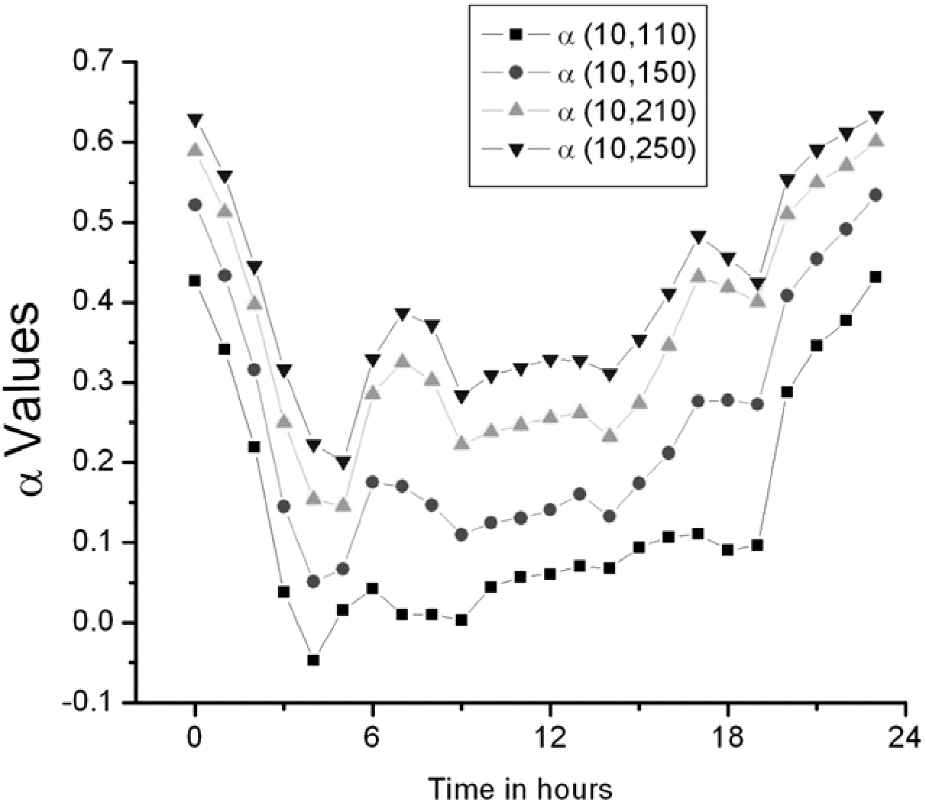

Fig.6b: Diurnal Variation of for Different Step Changes when Z_0 = 10 m (2010 data alone).

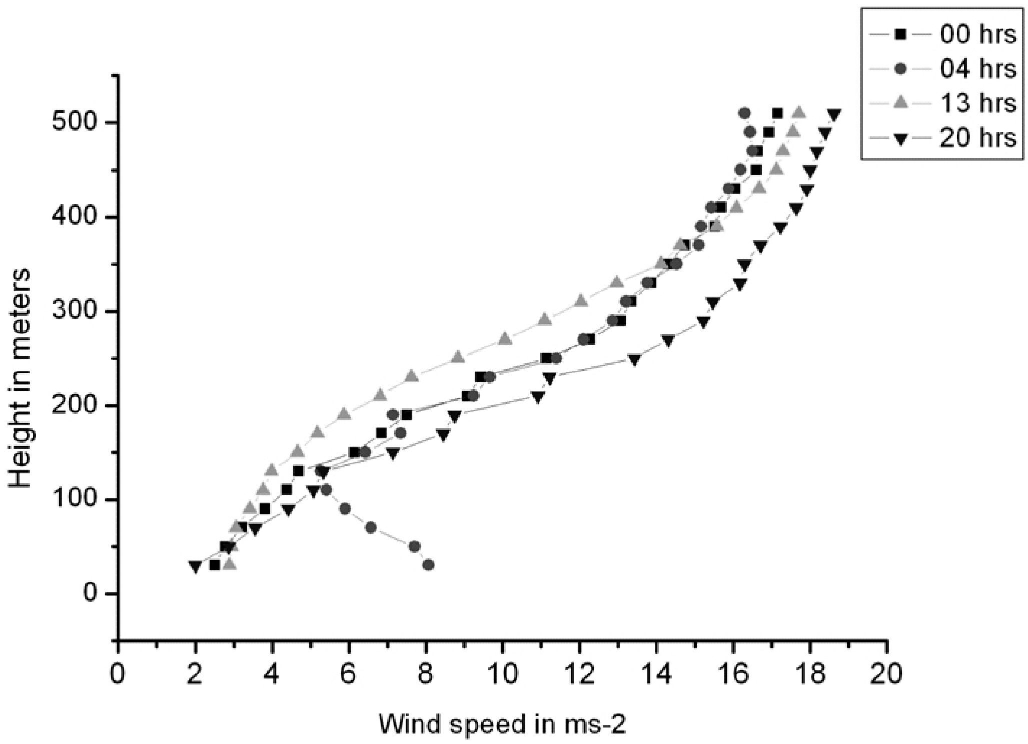

Fig.7: Mean Wind Speed Profile Over the Station for Different Times of the Day (whole data).

Monthly Variation of

The mean variation of as a function of the month of the year separated into the two seasons is presented in Table 2 and the averaged value across the heights up to height 500 m is as shown in Fig 8. The estimated number of hourly data points is enclosed in brackets. Power outages and mechanical faults of the sodar are responsible for the sparse data in the dry months. It is shown that the wet months have higher values than the dry months; unlike what is observed by Pashardes and Christofides (1995) that winter months records higher mean wind speeds than the summer months although they noted that the difference is not significant. This implies that stronger upper level wind speeds are to be expected during wet months than during the dry months. While this information serves as precaution for civil engineers in building skyscrapers, it is indeed an advantage in wind energy generation meaning greater energy during the wet months.

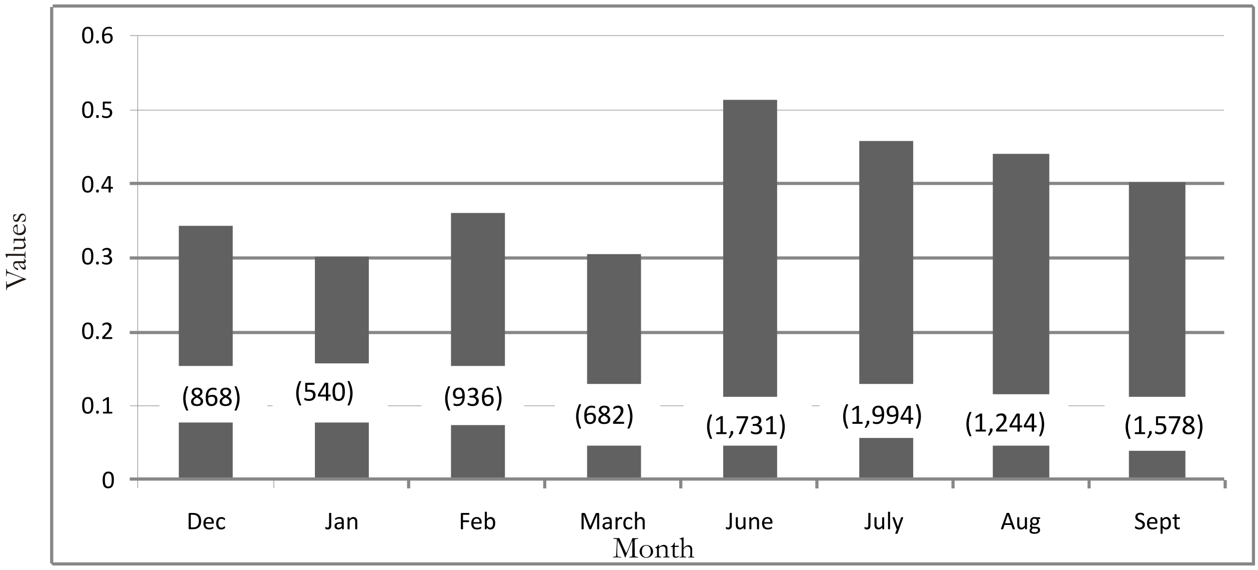

Fig 8: Variation of With Month Averaged Over the Entire Period and Height up to 500 m

Table 2: Mean Variation of With Height (Z_0 = 30 m) for Two Seasons of the Year Averaged Over the Entire Period and Height up to 500 m

Heights (m)	Dry Months					Wet Months				
	Dec	Jan	Feb	March	Mean	June	July	Aug	Sep	Mean
50	-0.05	-0.20	-0.04	-0.11	-0.10	0.04	0.00	0.03	0.12	0.05
70	-0.18	-0.22	-0.10	-0.18	-0.17	0.09	0.05	0.01	0.04	0.05
90	-0.09	-0.14	-0.01	-0.11	-0.09	0.21	0.14	0.07	0.07	0.12
110	0.04	-0.05	0.07	-0.07	0.00	0.25	0.18	0.13	0.10	0.17
130	0.05	-0.03	0.13	-0.01	0.03	0.27	0.20	0.14	0.13	0.18
150	0.22	0.15	0.24	0.10	0.18	0.43	0.36	0.34	0.27	0.35
170	0.30	0.23	0.31	0.20	0.26	0.49	0.42	0.41	0.34	0.41
190	0.31	0.23	0.36	0.24	0.29	0.49	0.43	0.42	0.35	0.42
210	0.39	0.36	0.41	0.31	0.37	0.56	0.51	0.49	0.44	0.5
230	0.38	0.34	0.42	0.33	0.37	0.57	0.53	0.52	0.45	0.52
250	0.45	0.43	0.46	0.41	0.44	0.62	0.56	0.55	0.50	0.55
270	0.47	0.46	0.47	0.43	0.46	0.64	0.58	0.56	0.51	0.57
290	0.48	0.48	0.50	0.45	0.48	0.64	0.58	0.57	0.51	0.58
310	0.48	0.48	0.49	0.46	0.48	0.65	0.59	0.57	0.53	0.58
330	0.49	0.48	0.50	0.47	0.48	0.65	0.59	0.58	0.53	0.59
350	0.50	0.48	0.50	0.49	0.49	0.65	0.60	0.58	0.54	0.59
370	0.49	0.48	0.50	0.48	0.49	0.65	0.60	0.58	0.54	0.59
390	0.51	0.48	0.50	0.49	0.49	0.64	0.59	0.58	0.54	0.59
410	0.51	0.47	0.49	0.50	0.49	0.63	0.59	0.58	0.54	0.59
430	0.50	0.47	0.49	0.50	0.49	0.63	0.59	0.57	0.54	0.58
450	0.50	0.46	0.50	0.50	0.49	0.63	0.58	0.57	0.54	0.58
470	0.51	0.47	0.49	0.50	0.49	0.63	0.58	0.57	0.53	0.58
490	0.50	0.45	0.49	0.49	0.48	0.62	0.58	0.56	0.53	0.57
510	0.50	0.46	0.48	0.49	0.48	0.61	0.57	0.56	0.52	0.57
Mean	0.34	0.3	0.36	0.31	0.33	0.51	0.46	0.44	0.4	0.45

CONCLUSION

The power law wind profile has been studied over Ile-Ife (7.52° N and 4.52° E) Nigeria using an acoustic sounder technique (METEK PCS 2000 mini sodar). The power law wind exponent being the parameter needed in extrapolating the wind speed above the surface from the available surface wind speed have been found to vary with a number of parameters.

Power law wind exponent increases with increasing height but tends towards a constant value at heights above 500 m, it decreases with increasing surface wind speed, and its values are higher at nights than at day-time. However, it has its minimum value between 0400 and 0500hrs. Relatively, its values are higher during the wet months than the dry months and its average value for the dry months being 0.33 while its average value for the wet months is 0.45.

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