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Investigation of Vertical Wind Shear Characteristics Using 50m Meteorological Tower Data

Sardar Maran, P.*

Assistant Professor, Centre for Earth & Atmospheric Science Sathyabama Institute of Science and Technology, Chennai, India

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Abstract

Wind measurement is important for estimating wind energy potential, but it is relatively cost-intensive and often conducted at a narrow height from the ground level. The typical range of most turbine hub heights is from 30-50 m or even higher. Extrapolation on wind data thus becomes necessary to estimate the wind speed at different heights. Doing so requires the essential understanding of wind shear characteristics representative to a location or a region. The analysis is carried out from the vertical profile of meteorological observation collected from 50 m tower at Sathyabama University during the period of 2010-2014. The tower is located near the coastal region in Chennai. The tower is equipped with instruments to measure several meteorological variables. For wind speed and direction, they are routinely measured at different heights, which are considered well suitable for wind shear characterization. In this work, the characteristics of wind shear exponent at the tower were investigated and discussed, with emphasis on temporal (diurnal and monthly) variation and spatial distribution.

Keywords: Wind Energy, Wind Shear, Surface Roughness, Meteorological Tower.

1. Introduction

Wind power has received continued interest worldwide because it is abundant and clean (i.e., non-polluting), and its utilization does not contribute to global warming. Wind energy development has been active and continued in Tamil Nadu. The effective and successful development of a wind energy program depends significantly on the availability of winds. Thus, the wind resource of an area or a region of interest for wind energy application needs to be assessed. Various methods of wind resource assessment have been proposed, ranging from measurement methods to computer simulation techniques (Landberg et al., 2003). Measurement methods are straightforward and desirable but relatively cost-intensive. Wind Resources and Environment, Tamil Nadu, have been established for wind measurement, which is often conducted at a limited height from 2-10 m, although the range of most wind turbine hub heights is 30-50 m or even higher. Several meteorological and wind monitoring programs are present in Tamil Nadu and operated or owned by governmental and non-governmental organizations (Farrugia, 2003). However, most of them are limited to near-ground measurement.

Analyzing the relationship between the environment and the atmosphere on a local scale is complicated on a meso-scale concept. The sea breeze is a meso-scale occurrence (Oke, 2006), up to 100 km confirmed to the coastal environment. The local vegetation and aerodynamic characteristics of land surface directly affect the transport of momentum, energy and substances between land surface and atmospheric boundary layer. Therefore, the subject of every kind of process on land surface becomes essential (Stull, 1988 and Hosomia et al., 1997). Atmospheric boundary layer and surface parameters are mostly important in air pollution dispersion analysis. Many pollution sources and their dispersion come about within the roughnesses of surface layer in the lower atmosphere. The roughness length is essential in determining wind shears over a surface and manipulating mechanical turbulence development. An enhancement of large roughness value increases surface friction and this increases vertical turbulent mixing and affect vertical wind shear.

In case of lack of wind measurement at a height above the ground surface, extrapolation of wind speed measured near the ground is often made, which typically use the following well-known power-law wind profile relationship (Rehman and Al-Abbadi, 2005).

*Corresponding author: sardarmaran@gmail.com

$$U_2/U_1=(Z_2/Z_1)^{\alpha} \text{ or } \alpha= \ln(U_2/U_1) / \ln(Z_2/Z_1) \quad (1)$$

where U_1 and U_2 are the wind speeds at heights (above the ground) Z_1 and Z_2, respectively, α is the wind shear exponent or coefficient (shortly, the shear exponent). A typical value of 1/7 (or ~ 0.14) for α is often adopted when no recommendation for other specific values is available.

The relationship in Equation (1) with α = 1/7 is customarily called the $1/7^{th}$ power law, and it generally well describes wind profiles within 50 m above the ground for near-neutral conditions (Gryning et al., 2007).

In Tamil Nadu, to the author's knowledge, there has not been much investigation of wind shear characteristics. The 50 m instrumented meteorological tower is located in Sathyabama University located in the coastal areas (Lattitude.12°52'23.14"N, Longitude 80°12'57.19"E) of Chennai. The primary objective of this tower monitoring program is to provide long-term meteorological data in the lower atmosphere at heights up to 50 m (above the ground) to support air quality management (Paton and Manomaiphiboon, 2013). Each tower is equipped with various instruments to measure several meteorological variables, which are wind speed and direction, temperature, humidity, radiation, and rainfall. Wind speed and direction are measured using at five different heights (2, 8, 16, 32 and 50 m), which is considered well suitable for the wind shear study. An example of wind shear study using data from tall towers can be seen in (Schwartz and Elliott, 2006). In this work, the characteristics of the shear exponent for this station were investigated, with emphasis on temporal (diurnal and monthly) variation and overall occurrence of time distribution.

2. Methodology

Five years (Jan., 2010 - Dec., 2014) of ten minutes wind data from the tower is obtained and used in the investigation here. Equation (1) was employed to determine the shear exponent. The quality of wind data measured at 50 m, 32 m, 16 m, 8 m, and 2 m was analysed by the National Institute of Wind Energy (NIWE), considered and screened that were good and reliable. This is believed to be caused by disturbances from structures or objects on the ground. Figure 1 shows the terrain map of the area.

Figure 1. Terrain map of the area.

2.1. Determination of Wind Shear

The main objective of this paper is to identify the vertical wind shear models and procedures that decrease the uncertainty correlated with wind shear analysis. Measuring a wind shear using remote sensing and tall wind turbine sites are more expensive than an instrumented meteorological tower. In the estimation of wind resources, the use of wind shear models added with uncertainty. The most commonly used methods of estimating wind shear are known as the log law and the power law. The surface roughness length is a parameter used to characterize shear and is also the height above ground level where the mean wind velocity is zero. The surface roughness values for various types of terrain are listed in Table 1.The power law exponent values for different types of terrains are listed in Table 2.

Table 1. Surface roughness values for various types of terrain. (Source: Wind Resource Assessment of India).

Terrain Description	Surface Roughness Length, zo (m)
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.01
Fallow field	0.03
Crops	0.05
Few trees	0.1
Many trees, hedges, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
Centers of cities with tall buildings	3.0

Table 2. Power law exponent values for different types of terrain.

Terrain Description	Power law exponent, α
Smooth, hard ground, lake or ocean	0.10
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22 – 0.24
Wooded country – small towns and suburbs	0.28 – 0.30
Urban areas with tall buildings	0.4

2.2. Wind Shear Analysis

The wind speed measured at heights 2, 8 and 16 m were referred as the lower heights. The wind speed data at 32 m and 50 m are the highest levels compared to the lower levels.

2.2.1. Vertical wind speed profile

Over most natural terrain, the surface cover is not uniform and changes significantly from location to location. While atmospheric pressure gradient force is the major control of wind speed and direction in the ABL, winds near the ground are heavily influenced through frictional drag imposed by surface roughness (Oke, 1987). This frictional drag causes turbulence, giving rise to a sharp decrease in wind speed as the underlying surface is approached. The height at which this frictional drag influence is felt is related to the size and distribution of the underlying surface elements. Theoretically, roughness length z_0 is defined as the height in meters above the ground level in which the mean wind speed becomes zero when the logarithmic wind speed profile is extrapolated downwards through the surface layer (Huschke, 1989). As z_0 is observed to increase with the average height and spacing of individual elements of the ground cover, such as trees or houses, it is often defined in this fashion. An alternative but related definition suggests that z0 is the size of turbulent eddies on the ground surface created when winds are disrupted by items on the surface; where larger z_0 values indicate larger eddy mixing, and likely larger surface objects (Panofsky and Dutton, 1984).

The atmospheric surface layer closest to the earth, in general whose height normally ranges from 2 to 200 m above the ground is influenced by contact with the earth's surface. The lowest 10% of the atmospheric boundary layer, called the surface layer is where turbulence and friction drag from the ground are the most considerable effects (Huschke, 1989). The surface layer of the ABL has been broadly studied due to its ease of access and significance, as all human being life resides in this layer. The studies observed on these characteristics were often reliable and were used to form the basis of the similarity theory principles that are used today in defining the characteristics of vertical wind profiles within ABL (Stull, 1988). Precise scaling relationships (such as the Monin-Obukhov similarity theory) were developed for the surface layer and consequently verified to be accurate when the winds are not calm, and in heights between 10 to 200 m above ground (Panofsky et al., 1977). These resemblance relationships began to function as the groundwork for the scientific study of the most important feature of the surface layer for wind energy developers and air quality managers. Two types of models are most extensively used in practice: the logarithmic and the power law models.

2.2.2. Surface Roughness Length

Roughness length has usually been estimated for local sites from vertical wind profiles and micrometeorological theory. The wind speed increases as the height increases. The frictional forces play a significant role when dealing with wind velocity profile even though they were caused by the surface layer of the earth, which is called roughness length. Logarithmic profile is the common profile to represent wind speed in atmospheric boundary layer. The influence of z_0 on the logarithmic wind profile is significant. When z_0 is small, the wind profile increases rapidly with height over a short length, and then is relatively uniform above that height. When z0 is large, the profile has a slow and smooth increase with height (World Meteorological Organization, 1981).

3. Results and Discussion

This section provides detailed monthly mean wind speed, cumulative distribution function, vertical wind shear profile and surface roughness at 2, 8, 16, 32 and 50 meters for 2010-2014. Tables 3 and 4 show the wind speed and wind directions values at 50 m level during south-west and north-east monsoon periods for the years 2010 to 2014.

Table 3. Mean wind speed and wind direction values during south-west monsoon for the years2010 to 2014.

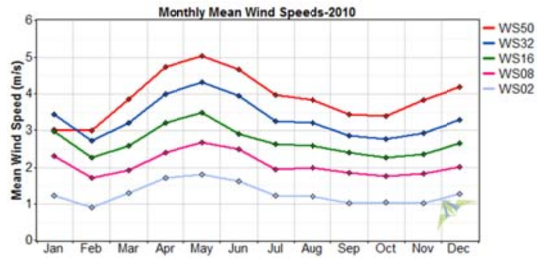
Year	JUNE		JULY		AUG		SEP	
	WS	WD	WS	WD	WS	WD	WS	WD
2010	4.7	213	4.0	218	3.9	223	3.5	217
2011	4.6	225	4.4	227	4.1	224	4.0	222
2012	4.2	210	4.3	214	5.2	216	3.6	215
2013	5.0	245	4.1	254	4.5	222	4.1	222
2014	4.8	219	5.1	227	4.1	217	3.8	219

Table 4. Mean wind speed and wind direction values during North-east monsoon for the years 2010 to 2014.

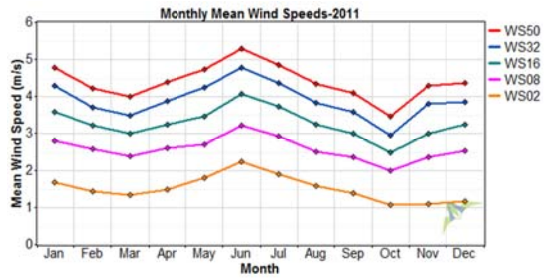
Year	OCT		NOV		DEC	
	WS	WD	WS	WD	WS	WD
2010	3.1	215	3	133	3.2	178
2011	2.6	189	3.5	138	3.6	146
2012	3.6	154	3.5	157	3.3	100
2013	3.4	204	3.1	125	3.9	147
2014	2.5	178	3.8	168	7	128

3.1. Monthly Wind Speed Profile

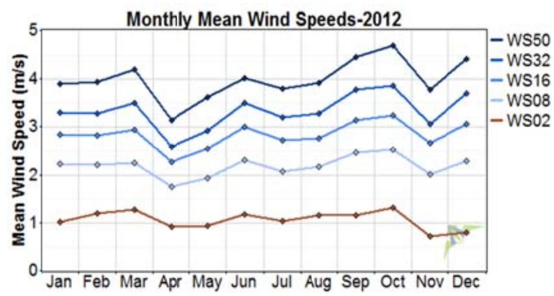
The monthly mean wind speed analysis carried out for five years from 2010 to 2014 at all levels from ABL and depicted in Figure 2(a-e). In 2010, the mean wind speed, gradually increases from February to May and reduces up to October. The highest mean wind speed of 5 m/s occurs in the month of May in the 50 m level. In 2011, the highest mean wind occurs at the month of June. The wind speed gradually decreased from January to March and then increasing. From June to October it decreases. The mean wind speed has the value of 4 m/s in March in 2012 and suddenly reduces to the month of April and gradually increases. In October, the wind speed increased up to 4.5 m/s. From January to June the wind speed increased from low level of 3m/s to the highest wind speed occurs at 5 m/s, after that it is reduced to lower speeds. The wind speed of 5.2 m/s occurs has the highest in the month of July in 2014 and gradually decreases after that.



(a)



(b)



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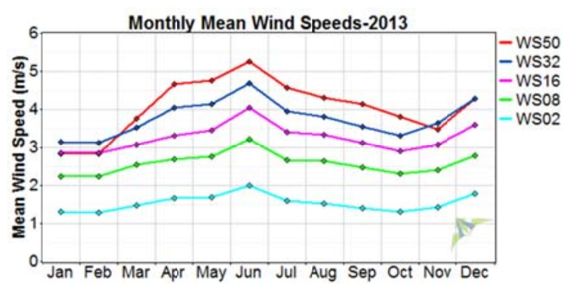

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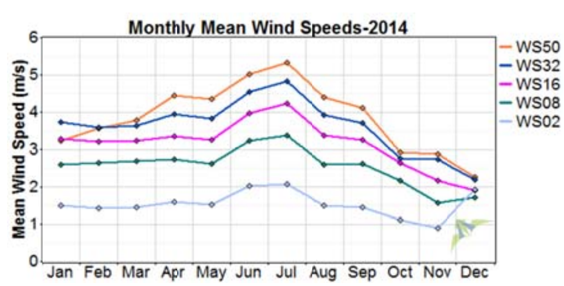

(e)

Figure 2. Monthly mean wind speed profiles for years 2010 to 2014.

3.2. Vertical Wind Shear Profile

For extrapolating the energy resources, the power law and log law proved to be preferable at different heights. Power law exponents or logarithmic fits differ in wind speed profiles and there is an uncertainty, according to the hub-height wind speeds of lower height anemometer data. The power law exponents vary by the function of location, time and other factors. In this study, the power law and the log law exhibit a good accuracy for roughness and shear coefficient and have the same certainty as shown in Figure 3. The shear parameter is dependent on atmospheric stability and ideally determined in different atmospheric regimes. The wind shear is near to a typical power law exponent value. Shear exponents developed from five years of data are applied to determine the robustness of the power law method.

3.3. Surface Roughness

Frictional forces act as an important role in wind speed profile. The frictional forces are at the base of the surface layer of atmosphere that depends on roughness length. The general profile to represent wind speed in atmospheric surface layer profiles is logarithmic profile. Roughness length and wind shear profile for different wind directions for the years 2010 to 2014 were analysed over the site (Figure 4). Local meteorological roughness associated with studies conducted using the experimental data obtained with 50 m tower. Various factors affect the vertical wind shear, either directly or indirectly including roughness, stability wise and wind direction. The ground roughness length indicates the degree to which wind is slowed down by friction as it passes close to the ground (Martano, 2000). The wind is slowed down in rougher ground as the roughness length is large. In this study the roughness length is analyzed for every month that occurs 3 to 4 meters ABL for five years, which refers to landscapes with many trees and buildings.

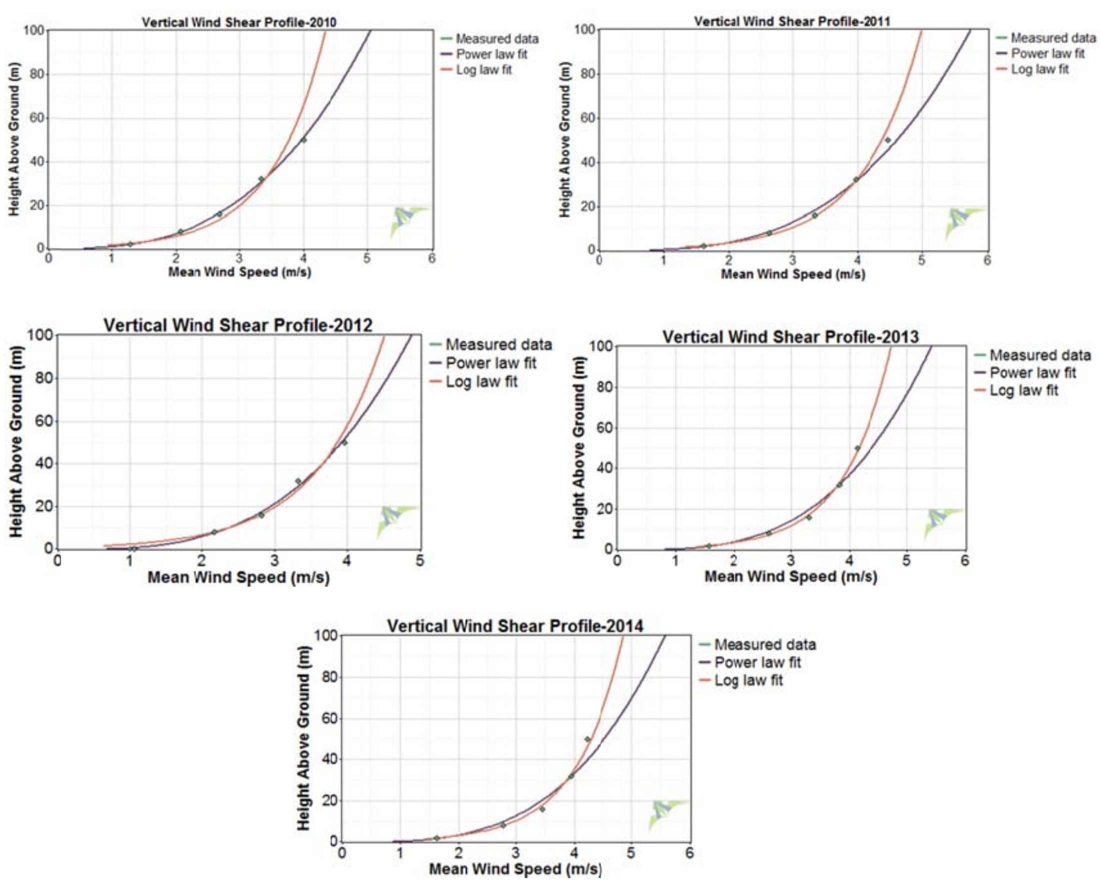

Figure 3. Vertical wind profiles for years 2010-2014.

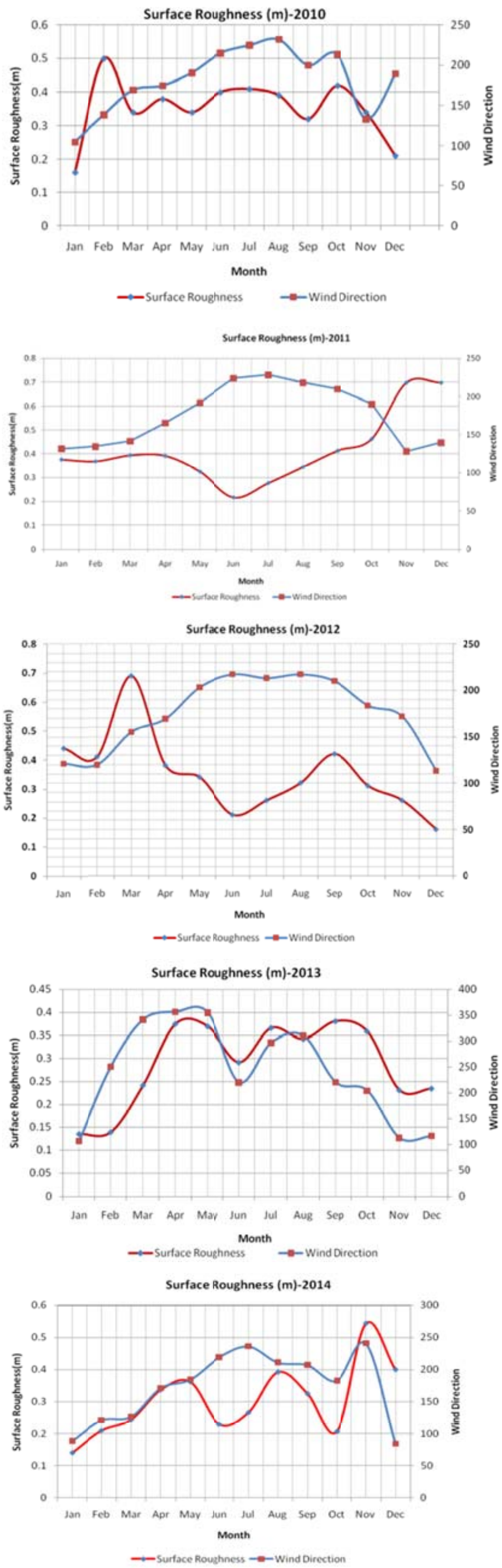

Figure 4. Surface roughness for years 2010 to 2014.

4. Conclusions

The work carried in this study is near an urban coastal area at Sathyabama University. The wind shear coefficient has been determined and the effect of vertical wind shear on velocity has been analyzed. The power law is in good agreement to the real surface layer wind profile near the coastal smooth terrain. There is a significant influence of land-sea interface that shows lower wind shear coefficient during sea breeze conditions than in land breeze. The months of March to June show higher values of wind shear component, the other months show lower values. The variation of wind shear with different directional sector emphasized the major role played by the topography and land use. Roughness length is strongly dependent on wind direction, as upstream topographic features are more relevant to local turbulence in horizontal winds, rather than local topographic features. Low and high values are clearly observed during onshore and offshore flows. The characteristics of roughness length and its variations strongly affected the land-sea interface in different sectors.

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