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Original Article

Meteorological tower wind shear characteristics, vertical wind speed profile, and surface roughness analysis near the coastline of Chennai

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Abstract

Extrapolation of wind data is required to estimate wind speeds at high altitudes. Doing so requires an essential understanding of wind shear characteristics related to the location or region. An analysis was carried out from the profile of meteorological data collected from a 50-m tower at Sathyabama Institute of Science and Technology which is near the coastline of Chennai, Tamil Nadu, India during the years 2010-2014. In this work, the analyzed data collected from an instrumented meteorological tower included the wind shear characteristics, vertical wind speed profile, and surface roughness. The characteristics of wind shear exponent at the tower were investigated with emphasis on temporal (diurnal and monthly) variation and occurrence distribution. The power law was derived at this location and it was in good agreement with the real surface layer wind profile near the smooth coastal terrain. There was a significant influence of the land-sea interface that showed a lower wind shear coefficient during sea breeze conditions than in land breeze.

Keywords: wind energy, wind shear, surface roughness, meteorological tower

1. Introduction

Wind power has received continued interest worldwide for the reasons that it is abundant and clean, i.e. non-polluting, and its use does not contribute to global warming. Wind energy development has been active and continues in Tamil Nadu, India. The effective and successful development of a wind energy program depends significantly on the availability of wind energy potential. 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 that range from measurement methods to computer simulation techniques (Landberg *et al.*, 2003). Measurement methods are straight-forward and desirable but relatively cost-intensive. The Wind Resources and Environment at Tamil Nadu was established to measure the characteristics of the wind but the measurements are often conducted at a limited height near or not far from the ground, i.e. 2-10 m. However, the heights of most wind turbine hubs in the current wind turbine technology are 30-50 m or even higher. Several meteorological and wind monitoring programs are present in Tamil Nadu and are operated or owned by the governmental and non-government organizations (Farrugia, 2003). However, most of them are limited to near-ground measurements.

Analyzing the relationship between the environment and the atmosphere on a local scale is complicated based on a meso-scale (Davies, Jakob, May, Kumar, & Xie, 2013). A sea breeze is a meso-scale occurrence (Oke *et al.*, 2005) that is unique for a coastal environment (Coffer & Parker, 2015). The local vegetation and aerodynamic characteristics on the land surface directly affect the transport of energy and substances between land surface and the atmospheric boundary layer. Therefore, the subject of every kind of process on land surface becomes essential (Stull, 1988). The atmospheric boundary layer and surface parameters are mostly important in an analysis of air pollution dispersion. Many pollution sources and their dispersions come about within the roughness surface layer in the lower atmosphere. The roughness length is essential in determining wind shear over a surface and

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manipulating mechanical turbulence development. A huge roughness length increases surface friction and this increases vertical turbulent mixing and wind shear.

To date, according to our knowledge, there have not been many investigations of wind shear characteristics in Tamil Nadu. A 50-m instrumented meteorological tower is located at the Sathyabama Institute of Science and Technology which is located in the coastal area 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 ground level) to support air quality management. Each tower is equipped with various instruments to measure several meteorological variables that include wind speed and direction, temperature, humidity, radiation, and rainfall. Wind speed and direction are measured at five different heights, i.e. 2, 8, 16, 32, and 50 m, which are considered quite suitable for a wind shear study. An example of wind shear study using data from tall towers can be seen in wind shear modelling (Liu & Liu, 2015). In that reported work, the characteristics of the shear exponent for each station were investigated with emphasis on temporal (diurnal and monthly) variation and overall occurrence distribution. The Sathyabama Institute of Science and Technology has a tower to study the potential wind power throughout the year. However, it is not possible to produce wind power in this area because the average wind speed at the most is 5 m/s. Since the wind speed increases at higher altitudes, the study was carried out at the higher levels only.

2. Methodology

The 50-m instrumented meteorological tower was erected at Sathyabama Institute of Science and Technology in January 2010. The tower is located at latitude 12° 52' 23.22 and longitude 80° 12' 57.12 with an elevation of 6 feet above sea level. It was partially funded by Indira Gandhi Centre for Atomic Research (IGCAR), Department of Atomic Energy, Government of India. Data collection starting from 1 February 2010 and has continued to the present. The data collection percentage was good up to the current date. The reliability and accuracy of analyzing the parameters were ensured every three months by the Scientists of Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. The raw data recovery rate was 90% and after quality assurance the percentage of good data was 86%. Missing data were ignored and the ten-minute wind speed data were normalized to get better results.

For the five years from January 2010 to December 2014, the ten-min wind data from the tower was obtained and used in the investigation to determine the shear exponent. The quality of wind data measured at 50 m, 32 m, 16 m, 8 m, and 2 m were screened and considered to be good and reliable. Since the data can be affected by disturbances from structures or objects on the ground, the following rules were applied in the screening as part of data quality checking:

- Speed at 32 m < Speed at 50 m
- Speed at 16 m < Speed at 32 m
- Speed at 8 m < Speed at 16 m
- Speed at 2 m < Speed at 8 m
- Difference of direction at 32 m and direction at 50 m < 45 degree
- Difference of direction at 16 m and direction at 32 m < 45 degree
- Difference of direction at 8 m and direction at 16 m < 45 degree
- Data at ten-min intervals with no missing values on both speed and direction

2.1 Determination of wind shear

The main objective of this paper was to identify the vertical wind shear models and procedures that decrease the uncertainty correlated with a wind shear analysis (Di Giuseppe & Tompkins, 2015). The leading industry software Windographer was used for the analysis of the wind resource data measured by MET tower software. It imports all common data formats, allows manual and automatic quality control, and performs sophisticated statistical analyses. Measuring 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 adds some 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 wind velocity is zero. The surface roughness length varies according to the terrain of the location and normally use surface roughness lengths.

For wind measurements at high levels, extrapolation of wind speed is measured near the ground by the well-known power-law wind profile relationship (Rehman, 2005)

$$U^2/ U^1= (Z^2/ Z^1)^{\alpha} \text{ or } \alpha= \ln(U^2/ U^1) / \ln(Z^2/ Z^1)$$

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), and ln is the natural logarithm. 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 with α=1/7 is customarily called the $1/7^{th}$ power law, and it generally gives a good description of wind profiles within 50 m above ground level for near-neutral conditions (Pramitha *et al.,* 2015).

2.2 Wind shear analysis

The wind speeds measured at the heights of 2, 8, and 16 m were considered the lower heights. The wind speed data at 32 m and 50 m were the higher levels compared to the lower levels. The instruments that measured the meteorological parameters in the 50-m meteorological instrumented tower are listed in Table 1. The values of temporal variation of wind shear component are shown in Table 2.

2.2.1 Vertical wind speed profile

The atmospheric surface layer closest to the earth is generally in a height range of 2-200 m above the ground and is influenced by contact with the earth's surface. The lowest 10% of the atmospheric boundary layer (ABL) is called the surface layer where turbulence and friction drag from the ground have considerable effects (Pilorz, Laskowski,

Table 1. Instruments used for all meteorological parameters in the 50 m tower.

Sl. No	Parameter measured	Type/ Make	Range	Installed levels (in m)	O/P Range in volts
1	Wind Speed	NRG#40 Hall Effect	1 m/s to 96 m/s	2, 8, 16, 32, 50	Digital Pulses
2	Wind Direction	NRG #200P	0 to 350 Degrees	2, 8, 16, 32, 50	0 to 5V
3	Relative humidity and temp sensor	Rotronic MP100H	-40 °C to +50 °C	2, 8, 16, 50	0 to 5V
4	Atmospheric pressure	RM Young 61202V	800 to 1060 hPa	Surface	0 to 5V
5	Precipitation	RM Young 61202V	0.1 mm/pulse	Surface	Digital Pulses
6	Nuclear Radiation	GM Tube ZP1220/01	0 to 3000 usv/h	Surface	-

Table 2. Temporal variation of wind shear component.

Month / Year	2010	2011	2012	2013	2014
Jan	0.4	0.3	0.3	0.2	0.3
Feb	0.3	0.4	0.4	0.2	0.3
Mar	0.3	0.4	0.4	0.2	0.3
Apr	0.3	0.3	0.3	0.3	0.3
May	0.3	0.2	0.3	0.3	0.3
June	0.3	0.3	0.2	0.3	0.2
July	0.3	0.3	0.2	0.4	0.2
Aug	0.3	0.2	0.3	0.3	0.3
Sept	0.3	0.3	0.3	0.3	0.3
Oct	0.3	0.3	0.3	0.3	0.2
Nov	0.3	0.4	0.2	0.3	0.2
Dec	0.3	0.4	0.3	0.35	0.2

Łupikasza, & Taszarek, 2015). The surface layer of the ABL has been broadly studied due to its ease of access and significance since all human life resides in this layer. The studies that observed 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 in ABL (Liu & Liu, 2015). 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 10-200 m above ground (Mahrt, 2000). 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 models that are extensively used in practice are the logarithmic and the power law models.

2.2.2 Surface roughness length

Over most natural terrain, the surface cover is not uniform and changes significantly from location to location. While atmospheric pressure gradient forces are 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 (Martano, 2000). This frictional drag cause's 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, $Z^0$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 extrapolated downwards through the surface layer (Hanafusa, Bum Lee, & Lo, 1986). 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 (Jackson, 1980). An alternative but related definition suggests that Z^0 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 (Holtslag, Bierbooms, & Van Bussel, 2014).

Roughness length has usually been estimated for local sites from vertical wind profiles and micro-meteorological 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. 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 stable above that height (World Meteorological Organization *et al.,* 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 m for the years 2010-2014.

3.1 Monthly wind speed profile

The monthly mean wind speed analysis was carried out for five years from 2010 to 2014 at all levels from ABL. In the year 2010 the mean wind speed gradually increased from February to May and then reduced to October. The highest mean wind speed of 5 m/s occurred in May at the 50 m level. In 2011 the highest mean wind occurs in the month of June. The wind speed gradually decreased from January to March and then increased. From June to October it decreased. The mean wind speed was 4 m/s in March in 2012 and suddenly reduced in April and then gradually increased. In October the wind speed increased up to 4.5 m/s. From January to June the wind speed increased from a low level of 3/ms to the highest wind speed which was 5 m/s and after that it reduced to a lower speed. The highest wind speed of 5.2 m/s occurred in July in 2014 and gradually decreased after that.

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 m for the years 2010-2014. Table 3 and Table 4 show the wind speed and wind directions at the 50 m level during the south-west and north-east monsoon periods for the years 2010-2014.

Table 3. Mean wind speed & wind direction values during south-west monsoon for the years 2010-2014.

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

Abbreviations: WS, wind speed; WD, wind direction

Table 4. Mean wind speed & wind direction values during north-east monsoon for the years 2010-2014.

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

Abbreviations: WS, wind speed; WD, wind direction

3.2 Vertical wind shear profile

The power law and large law proved to be preferable to extrapolate the energy resources at different heights (Khalfa, Benretem, Herous, & Meghlaoui, 2014). 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 current hub heights of a modern utility scale wind turbine generators that are available in the market today range from 80 to 150 m. The power law exponents vary by function of location, time, and other factors. In this study the power law and the log law exhibit good accuracy for roughness and shear coefficient and have the same certainty (Figure 1). The shear parameter is dependent on atmospheric stability and is ideally determined in different atmospheric regimes. The wind shear is near to a typical power law exponent value. Shear expo-nents 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 in the surface layer of the earth which is called the roughness length. The general profile to represent wind speed in atmospheric boundary layer profiles is a logarithmic profile. The roughness length and wind shear profile for different wind directions for the years 2010-2014 were analyzed over the site (Figure 2). Local meteorological roughness was associated with studies conducted using the experimental data obtained with the 50-m tower. Various factors affected vertical wind shear, either directly or indirectly including roughness, month wise, and

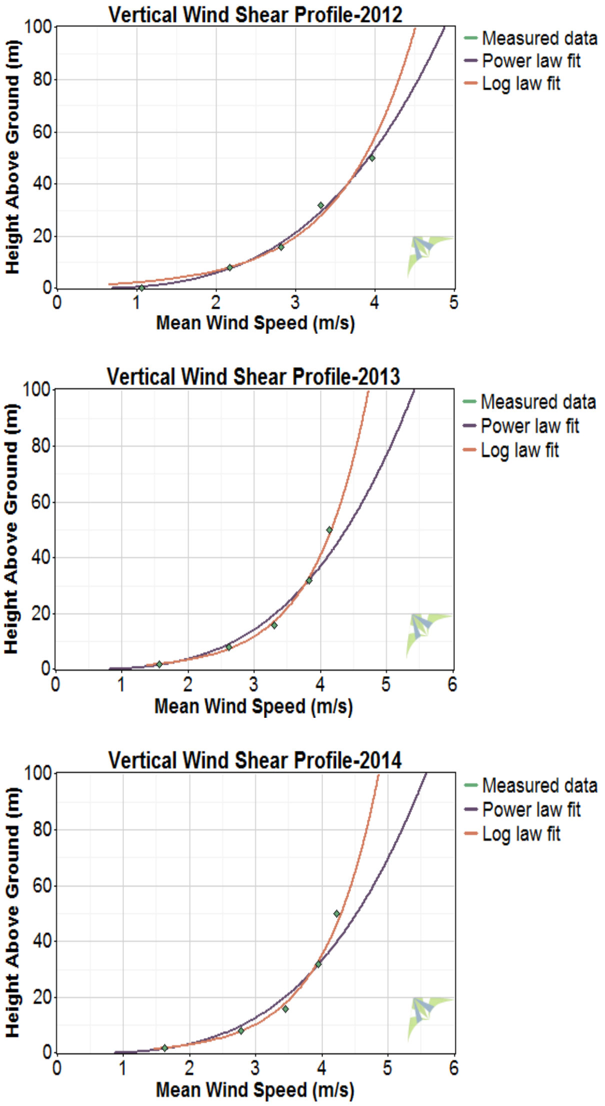

Figure 1. Vertical wind shear profile.

wind direction. The ground roughness length indicates the degree to which wind is slowed down by friction as it passes close to the ground. The wind is slowed down in rougher ground and the roughness length is large. In this study, the roughness length analyzed each month occurred 3 to 4 meters ABL for five years which referred to landscapes with many trees and buildings. The statistical analyses of power law and log law are shown in Table 5 and Table 6 in terms of root mean square error and mean average error.

4. Conclusions

This study was carried out near the urban coastal area at Sathyabama Institute of Science and Technology. The wind shear coefficient was determined and the effect of vertical wind shear on velocity was analyzed. The power law was in good agreement to the real surface layer wind profile near the smooth coastal terrain. There was a significant influence of land-sea interface that showed lower wind shear

Figure 2. Surface roughness.

Table 5. Statistical analysis of error for log-law.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MAE	2010	0.77	0.57	0.68	0.76	0.75	0.73	0.72	0.64	0.60	0.68	0.90	0.90
	2011	0.69	0.65	0.78	0.80	0.79	0.71	0.69	0.85	0.79	0.81	0.84	0.88
	2012	0.91	0.78	0.79	0.69	0.73	0.73	0.78	0.76	0.81	0.90	0.75	0.80
	2013	0.58	0.58	0.53	0.64	0.64	0.57	0.61	0.56	0.58	0.60	0.61	0.72
	2014	0.70	0.48	0.44	0.51	0.54	0.50	0.51	0.50	0.43	0.36	0.56	0.54

Abbreviation: MAE, mean average error

Table 6. Statistical analysis of error for power law.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RMSE	2010	0.92	0.69	0.76	0.82	0.83	0.80	0.79	0.72	0.69	0.76	0.90	0.90
	2011	0.68	0.90	0.84	0.63	0.89	0.90	0.85	0.69	0.72	0.78	0.89	0.87
	2012	1.22	0.83	0.85	0.77	0.80	0.80	0.84	0.84	0.87	0.97	0.80	0.85
	2013	0.72	0.71	0.63	0.69	0.71	0.65	0.68	0.62	0.64	0.68	0.76	0.85
	2014	0.87	0.64	0.56	0.58	0.62	0.57	0.58	0.57	0.51	0.46	0.67	0.68

Abbreviation: RMSE, root mean square error coefficient during sea breeze conditions than in the land breeze. The months of March to June showed higher values of the wind shear component. The other months showed lower values. The variation of wind shear in different directional sectors 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 were clearly observed during onshore and offshore flows. The characteristics of roughness length and its variation were strongly affected in land-sea interface sectors.

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