

Modeling the Variation of Wind Speed with Height for Agricultural Source Pollution Control

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ABSTRACT

Wind speed is an important parameter in modeling odor transmission from an agricultural source. It is common to measure wind speed at a single height above the ground, for instance 10 m. Since wind speed increases more rapidly with height, it is always necessary to interpolate this measurement to the height where the odor is sampled. This project investigated the variation of wind speed with height (0 m to 10 m) using data from weather stations and a precise airspeed probe. Five mathematical models were evaluated by means of statistical indices. The logarithmic model did not adequately describe the variation of wind speed at a height of 0 m to 10 m above the ground. The power law model was found more applicable with the exponent in the range of 0.3 to 0.6. Besides the logarithmic and power law models, the three-parameter exponential model can favorably fit wind speed vs. height. Wind data measured at 10 m can then be easily interpolated to any height from 0 m to 10 m using models with the estimated parameters in this research.

INTRODUCTION

The odor emitted from an agricultural source is carried to neighbors by wind. Wind speed changes considerably with height. Wind speed is an important parameter in modeling odor transmission. Accurate measurement of wind speed is necessary. Wind instruments are usually placed at a single height above the ground, for instance 10 m. Wind data are usually available from a wind instrument or the local weather station, but they are likely different from the site where the odor is emitted. It is usually necessary to interpolate this measurement to the height where the odor is sampled.

Great effort has been made to develop suitable analytical expressions relating wind speed to height (Wark and Warner 1976). Two models are most widely used in practice: the logarithmic and the power law models. They have been applied in studying the transport and dispersion of air pollutants as well as of odors (Strom 1976; Touma 1977; Irwin 1979; King 1982; Panofsky and Dutton 1984; Stern et al. 1984; Carney and Dodd 1989; Juda-Rezler 1989). Determination of values for the exponent in the power law model has also been the subject of much research (Sutton 1953; Strom 1976; Irwin 1979; Touma 1977; Simiu and Scanlan 1978).

However, most of the effort has been put on using these models for heights greater than 100 m. As we know, the wind speed increases more rapidly near the surface of the earth, up to 8 m (Humphreys 1920). This is the height of concern for odor transmission to neighboring residences from agricultural sources. No literature was found validating the models by using measured data near agricultural sources. Discrepancies exist in the literature when choosing the exponent term in the power law model (Wark and Warner 1978; Simiu and Scanlan 1978).

The objectives of this research were (1) to examine the value of the exponent term in the power law model, (2) to evaluate these models by using data collected from an experimental field weather station and an airspeed probe, and (3) to propose a new model for wind profiles up to 10 m.

MATERIALS AND METHOD

Models

Model 1: The Logarithmic Law. The logarithmic law is expressed as

$$u = \frac{1}{k} u_* \ln \frac{Z}{Z_0} \tag{1}$$

where u is the wind speed at height Z above ground, m/s; k is the von Karman constant equal to 0.4 (approximately); and Z_0

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is the ground roughness. Values of Z_0 can be found in many publications (Simiu and Scanlan 1978; Liu 1991; ANSI 1982). The term u_* is the shear velocity defined as

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \tag{2}$$

where τ_0 is the stress of wind at ground level and ρ is the air density.

Equation 1 can be expressed as

$$u = b_1 + b_2 \ln Z \tag{3}$$

where

$$b_1 = -\frac{1}{k} u_* \ln Z_0, \tag{4}$$

$$b_2 = \frac{u_*}{k}. \tag{5}$$

The relationship between wind speed at 10 m and wind speed at any height from 0 m to 10 m can be derived as follows. From Equation 1, for wind speed u at height Z:

$$u = \frac{u_*}{k} \ln \frac{Z}{Z_0} \tag{6}$$

For wind speed at the reference height, 10 m:

$$u_{10} = \frac{u_*}{k} \ln \frac{10}{Z_0} \tag{7}$$

Then

$$\frac{u}{u_{10}} = \frac{\frac{u_*}{k} \ln \frac{Z}{Z_0}}{\frac{u_*}{k} \ln \frac{10}{Z_0}} = \frac{\ln Z - \ln Z_0}{\ln 10 - \ln Z_0} = 1 + \frac{\ln \frac{Z}{10}}{\ln \frac{10}{Z_0}} \tag{8}$$

or

$$u = u_{10}\left(1 + b \ln \frac{Z}{10}\right) \tag{9}$$

where

$$b = \frac{1}{\ln 10 - \ln Z_0}. \tag{10}$$

It is seen that

$$b_1 = u_{10}, \quad b_2 = u_{10} b. \tag{11}$$

The logarithmic law comes from the turbulent boundary layer theory that has been developed based on numerous laboratory experiments. It has been regarded by some meteorologists as a superior representation of strong wind profiles in the lower atmosphere (Tennekes 1973; Pasquill 1972; Owen 1974). However, it has the inconvenience that the adjustment is needed of two parameters, u_* and z_0, which cannot be directly measured (Hertig 1995). It also produces an unreal negative speed at heights $Z < Z_0$. For these reasons, in engineering applications and in building codes/standards, the power law is used most often (Liu 1991). The power law is also favored among atmospheric physicists (Hertig 1995).

Model 2: The Power Law 1. The power law has the following form:

$$u = b_1 Z^{b_2} \tag{12}$$

where u is the wind speed at any reference height Z and b_1 and b_2 are fitting coefficients. The term b_2 is the power-law exponent, which depends on surface roughness and atmospheric stability.

The relationship between wind speed at 10 m and wind speed at any height from 0 m to 10 m is shown in Equation 13.

$$u = u_{10}\left(\frac{Z}{10}\right)^{b_2} \tag{13}$$

where u_{10} is the wind speed at 10 m above ground.

Table 1 shows results of previous research for the exponent term in the power law model. The data in Table 1 show: (1) large discrepancies exist (b_2 varies from 0.0 to 1.0), (2) one fixed value (1/7) for b_2 is likely to result in larger errors, and (3) a wide range for b_2 (0.0 to 1.0) may generate a difficulty over choosing a suitable value for use in evaluating odor dispersion from agricultural sources. Therefore, more research is necessary before applying any of the values of b_2 to the odor dispersion problems near the ground.

TABLE 1
Exponent For Power Law Wind Speed Profile

b_2	Reference
1/7	Sutton 1953
0.05 - 0.6	Irwin 1979
0.0 - 1.0	Wark and Warner 1976
1/7 - 0.40	Simiu and Scanlan 1978
1/10 - 1/3	ANSI 1982
0.07 - 0.55	Turner 1994
0.080 - 0.624	Touma 1977
0.1 - 0.8	Strom 1976

Model 3: The Power Law 2. Equation 14 is another form of the power law. There are three parameters in the model that could be adjusted during regression.

$$u = b_1 Z^{b_2} + b_3 \quad (Z > 0) \tag{14}$$

The logarithmic and the power functions are all basic functions. Another basic and simple function is the exponential function. The following models are proposed based on the exponential function and can be viewed as an alternative to express the relationship between wind speed and height.

Model 4: The Exponential Law 1. The simplest form of the exponential function is

$$u = b_1 e^{-b_2 Z} \tag{15}$$

Model 5: The Exponential Law 2.

$$u = b_1 e^{-b_2 Z} + b_3 \tag{16}$$

Models 1, 2, and 4 are two-parameter models. Models 3 and 5 are three-parameter models.

Parameter estimation method

The five models mentioned above can be expressed in the form:

$$\psi = \beta_1 + \beta_2 \ln Z \quad (17)$$

$$\psi = \beta_1 Z^{\beta_2}$$

$$\psi = \beta_1 Z^{\beta_2} + \beta_3$$

$$\psi = \beta_1 e^{-\beta_2 Z}$$

$$\psi = \beta_1 e^{-\beta_2 Z} + \beta_3$$

where ψ is the estimate of u, β_1 is the estimate of b_1, β_2 is the estimate of b_2, and β_3 is the estimate of b_3.

Nonlinear parameter estimation methods can be used to obtain the parameters in the models based on the measured data of u vs. height Z. In nonlinear estimation, the parameters are iteratively adjusted to minimize a goodness of fit of sum squared function (S) in order to achieve a global minimum. The Levenburg-Marquardt algorithm (Beck and Arnold 1977) was used in the computer program. This method provides a compromise between the steepest descent and Gauss methods with the initial iterations close to the steepest descent method and the final iterations close to the Gauss method. It can remove instability and reduce oscillations in searching the minimum (Beck and Arnold 1977).

The sum squared function can be expressed as

$$S = \sum_{i=1}^{n} (u_i - \psi_i)^2 \quad (18)$$

where n is the total number of measurements and i is an individual measurement.

The Levenburg-Marquardt algorithm requires the sensitivity matrix, which is a matrix of the partial derivatives of ψ with respect to the parameters. For a two-parameter model, the sensitivity matrix is:

$$X = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \\ \vdots & \vdots \\ X_{n1} & X_{n2} \end{bmatrix} = \begin{bmatrix} \frac{\partial \psi_1}{\partial \beta_1} & \frac{\partial \psi_1}{\partial \beta_2} \\ \frac{\partial \psi_2}{\partial \beta_1} & \frac{\partial \psi_2}{\partial \beta_2} \\ \vdots & \vdots \\ \frac{\partial \psi_n}{\partial \beta_1} & \frac{\partial \psi_n}{\partial \beta_2} \end{bmatrix} \quad (19)$$

For a three-parameter model, the sensitivity matrix is:

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \\ \vdots & \vdots & \vdots \\ X_{n1} & X_{n2} & X_{n3} \end{bmatrix} = \begin{bmatrix} \frac{\partial \psi_1}{\partial \beta_1} & \frac{\partial \psi_1}{\partial \beta_2} & \frac{\partial \psi_1}{\partial \beta_3} \\ \frac{\partial \psi_2}{\partial \beta_1} & \frac{\partial \psi_2}{\partial \beta_2} & \frac{\partial \psi_2}{\partial \beta_3} \\ \frac{\partial \psi_3}{\partial \beta_1} & \frac{\partial \psi_3}{\partial \beta_2} & \frac{\partial \psi_3}{\partial \beta_3} \\ \vdots & \vdots & \vdots \\ \frac{\partial \psi_n}{\partial \beta_1} & \frac{\partial \psi_n}{\partial \beta_2} & \frac{\partial \psi_n}{\partial \beta_3} \end{bmatrix} \quad (20)$$

The sensitivity coefficients of the models are derived and shown in Table 2. The method also requires starting values for the parameters in order to initiate the fitting. These values for the five models are obtained using pre-scan values specific to the input data. The convergence criterion is that the parameters are not changing significantly (<0.0001) for successive iterations. Four indices were used to evaluate the models. They were:

1. the minimized sum of squared function, S, which is the actual least squares measures of fit (the smallest S gives the best model);
2. sum of squared regression, SSR, which represents the sum of squares of deviations of the predicted values from the mean of the observations (the larger this value, the better the fit will be);
3. correlation coefficient R^2; and
4. standard error of the fit, SE, which is the actual least squares error of fit (the closer this value is to zero, the better the least squares fit will be).

TABLE 2
The Sensitivity Coefficients of the Models

Model	Sensitivity Coefficient		
	$X_{i,1}$	$X_{i,2}$	$X_{i,3}$
1	1	ln Z	-
2	Z^{β_3}	$\beta_1 Z^{\beta_3} \ln Z$	-
3	1	Z^{β_3}	$\beta_1 Z^{\beta_3} \ln Z$
4	$e^{-\beta_2 Z}$	$-\beta_1 Z e^{-\beta_2 Z}$	-
5	1	$e^{-\beta_2 Z}$	$-\beta_1 Z e^{-\beta_2 Z}$

Experimental facilities

Data were collected on a cloudy and windy morning starting from 9:30 a.m. The site was near a swine research unit in Ames, Iowa. Air temperature was 10.2°C (50.4°F), and relative humidity was 69.3%. The land was flat overall. The following instruments were used:

Weather Station. The weather station consisted of a wind speed sensor, a wind direction sensor, a temperature and relative humidity probe, and a solar radiation sensor. The wind speed sensor measured wind speed in the range of 0 m/s to 45 m/s (0 ft/min to 8858 ft/min). The accuracy was ±1.5%. The three-cup anemometer utilized a magnet-activated reed switch, which had a frequency proportional to wind speed. Wind speed data at 10 m above the ground were stored in a programmable datalogger in a small, rugged, sealed module and retrieved using a laptop computer. The wind speed sensor was calibrated by using the airspeed probe described below.

Airspeed Probe. The variation of wind speed with height was measured using a portable, hand-held instrument. The instrument used thermal anemometry to provide accurate air velocity measurements. The instrument had a programmable time constant. The display presented a steady, time-averaged velocity instead of the rapidly changing numbers typically found with fluctuating flows. The instrument had a velocity

TABLE 3
Measured Average Wind Speed Data Vs. Height

Test	Height (m) 0.1	1	2	2.5	3.5	4.5	10
	Wind speed (m/s)						
1	2.37	3.07	3.86	4.65	5.64	5.69	7.73
2	1.57	3.61	4.50	4.77	5.23	5.94	8.29
3	1.58	2.41	4.82	5.40	5.62	5.73	8.91
4	1.68	2.05	4.67	5.54	6.05	6.63	10.25
5	2.59	3.15	3.61	5.54	5.75	6.19	8.28
6	1.10	2.74	4.47	5.89	5.99	6.59	9.78

TABLE 4
Estimation of Parameters

Test	Model	β_1	sd	β_2	sd	β_3	sd
1	1	4.0307	0.3372	1.0982	0.2514	-	-
	2	3.4645	0.2519	0.3384	0.0446	-	-
	3	1.6709	0.6013	0.5640	0.1272	1.7426	0.6141
	4	3.3948	0.3762	−0.0872	0.0167	-	-
	5	−6.7658	0.7045	0.1789	0.0413	8.8779	0.7779
2	1	4.0176	0.3009	1.3276	0.2006	-	-
	2	3.4426	0.0896	0.3727	0.0157	-	-
	3	2.8463	0.3934	0.4282	0.0436	0.5787	0.3809
	4	3.3915	0.4428	−0.0939	0.0192	-	-
	5	−7.3409	0.8224	0.2024	0.0523	9.1384	0.8977
3	1	3.9993	0.4592	1.4829	0.3061	-	-
	2	3.2594	0.2913	0.4320	0.0526	-	-
	3	2.7417	1.2543	0.4849	0.1527	0.5178	1.2363
	4	3.3103	0.5419	−0.1035	0.0233	-	-
	5	−8.4264	1.3474	0.2043	0.0756	9.8318	1.4686
4	1	4.1847	0.6383	1.7353	0.4255	-	-
	2	3.1288	0.3174	0.5159	0.0576	-	-
	3	2.4522	1.0075	0.5951	0.1477	0.7192	1.0465
	4	3.3430	0.5834	−0.1166	0.0238	-	-
	5	−11.1727	1.7737	0.1628	0.05523	12.3913	1.9611
5	1	4.2837	0.4643	1.1736	0.3095	-	-
	2	3.6437	0.3663	0.3474	0.0615	-	-
	3	1.6881	0.9712	0.5888	0.2062	1.9115	1.0052
	4	3.5901	0.4489	−0.08864	0.01877	-	-
	5	−7.4050	1.5034	0.1739	0.0775	9.6214	1.6617
6	1	4.1169	0.4719	1.7707	0.3145	-	-
	2	3.2891	0.2233	0.4767	0.0391	-	-
	3	3.5950	1.1039	0.4497	0.0991	0.3103	1.0751
	4	3.4077	0.6345	−0.1106	0.0259	-	-
	5	−9.7356	0.9532	0.2208	0.0579	10.7016	1.0238

TABLE 5
Comparison of Five Models

Test	Model	*SSR*	*S*	R^2	*SE*
1	1	15.7173	4.1195	0.79	0.9077
	2	18.6384	1.1983	0.91	0.4896
	3	19.2728	0.5639	0.97	0.3755
	4	16.4456	3.3911	0.83	0.8236
	5	19.5232	0.3045	0.98	0.2759
2	1	22.9679	2.6214	0.90	0.7241
	2	25.4382	0.1512	0.99	0.1739
	3	25.4850	0.1043	0.99	0.1615
	4	20.7314	4.8579	0.81	0.9857
	5	24.9977	0.5917	0.98	0.3846
3	1	28.6567	6.1055	0.82	1.1050
	2	33.1387	1.6235	0.95	0.5698
	3	33.1998	1.5623	0.96	0.6249
	4	27.1376	7.6246	0.78	1.2349
	5	33.1334	1.6282	0.95	0.6379
4	1	39.2443	11.7952	0.77	1.5359
	2	48.9862	2.0533	0.95	0.6408
	3	49.1879	1.8516	0.96	0.6804
	4	41.6041	9.4354	0.82	1.3737
	5	49.6143	1.4251	0.97	0.5969
5	1	17.9482	6.2413	0.74	1.1172
	2	21.6588	2.5307	0.89	0.7114
	3	22.5219	1.6676	0.93	0.6457
	4	19.3265	4.8631	0.80	0.9862
	5	22.9197	1.2698	0.95	0.5634
6	1	40.8626	6.4459	0.86	1.1354
	2	46.3271	0.9813	0.98	0.4430
	3	46.3497	0.9588	0.98	0.4896
	4	36.4778	10.8307	0.77	1.4718
	5	46.3237	0.9848	0.98	0.4962

range from 0.15 m/s to 50.79 m/s (30 ft/min to 9,999 ft/min). Accuracy was 3.0% of reading or ±0.015 m/s (± 3 ft/min), whichever was greater.

Data Collection. The airspeed probe was used to measure wind speed at 0.1 m, 1 m, 2 m, 2.5 m, 3.5 m, and 4.5 m. The wind speed readings per height were averaged and recorded every 2.5 minutes. Measurements of wind speed at six different heights (0.1 m, 1 m, 2 m, 2.5 m, 3.5 m, and 4.5 m) took about 15 minutes. To minimize the effect of wind speed variability over the time, the same time period was used to average the wind speed value at 10 m. Wind speed data at 10 m above the ground were measured by the weather station. An averaged value of wind speed over 15 minutes was recorded.

Six sets of data were collected sequentially at the same location. Each test took about 15 minutes. Data used in this research are listed in Table 3.

RESULTS AND DISCUSSION

Table 4 shows the results of the parameter estimation. It is seen that the exponent term β_2 varies from 0.3 to 0.5 for the power law model 1 and 0.4 to 0.6 for the power law model 2. The results provide a narrow range of the exponent term in the power law model application. Wind data measured by weather stations at a height of 10 m can be easily interpolated to any height of 0 m to 10 m using models with the estimated parameters in Table 4. Table 5 shows a comparison of the models evaluated by four indices. Model 3 ranked the first for data sets 2, 3, and 6 because it resulted in the largest values of SSR and R^2 and smallest value of S. Model 3 also ranked the second to model 5, which resulted in the largest values of SSR and R^2 and smallest value of S for data sets 1, 4, and 5. Model 2 resulted in the smallest SE for tests 2 and 6. These results suggest that these three models are capable of expressing the relationship between wind speed and height. Considering all tests, model 3 is recommended as the best overall model.

Figures 1 and 2 show comparisons of the measured data with the model predictions for data sets 1 and 2, respectively. Model 1 was able to predict good results when height is decreased from 4.5 m but failed when height is increased. Model 4 was able to predict good results when height is increased from 4.5 m but produced a larger error when height decreased. Models 2, 3, and 5 were able to predict good results within the height range between 0.1 m to 10 m. Similar conclusions can be drawn for all six data sets. Figures 3 and 4 show the residual plots (difference between measurement and prediction) vs. height. No apparent pattern can be observed from the plots, which means no systematic error was involved.

Figures 5 through 9 show the plots of the measured data and predictions with 95% confidence limits for the five models for data set 2, which was arbitrarily chosen as an example for all data sets. The conclusions are similar for all data sets. It is seen that all data points fall within the 95% confidence limits except for one point in model 4. However, the ranges of 95% confidence limits are 6.5% to 87% for model 1, 9.5% to 16.5% for model 4, and 9% to 23.85% for model 5. These wide ranges may result in a larger uncertainty in the

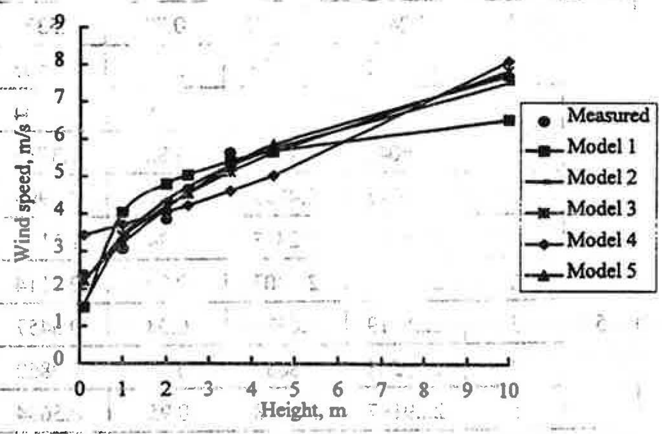

Figure 1 *Comparison of measured data with models for data set 1.*

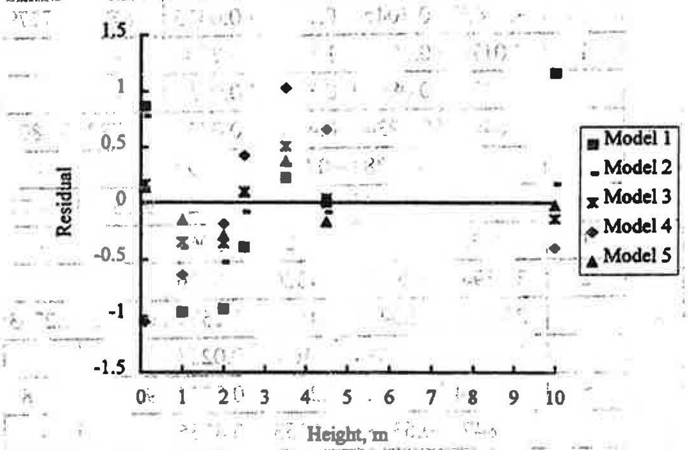

Figure 3 *Residual plot for data set 1.*

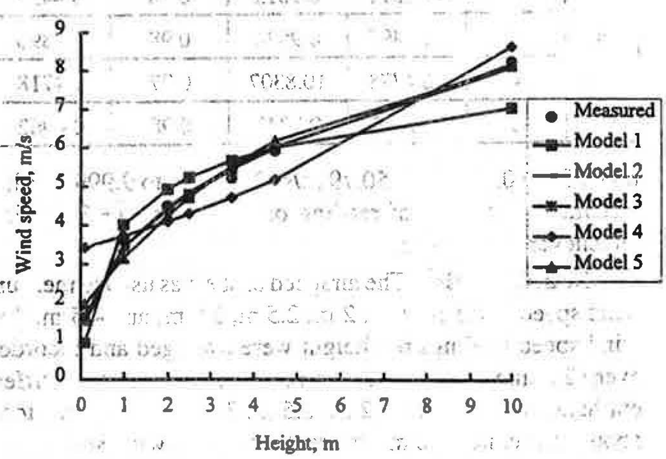

Figure 2 *Comparison of measured data with models for data set 2.*

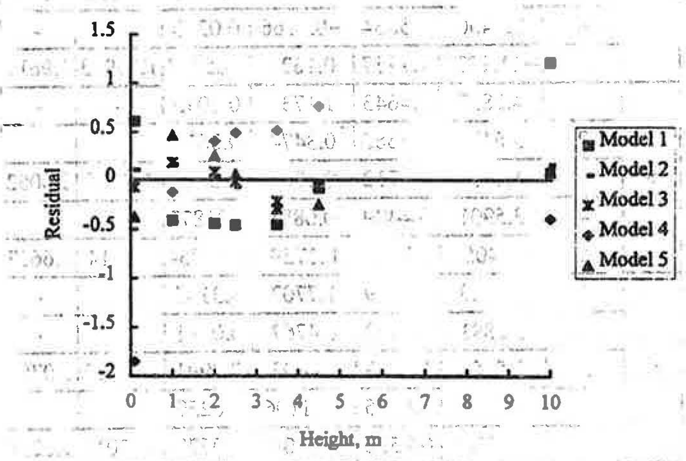

Figure 4 *Residual plot for data set 2.*

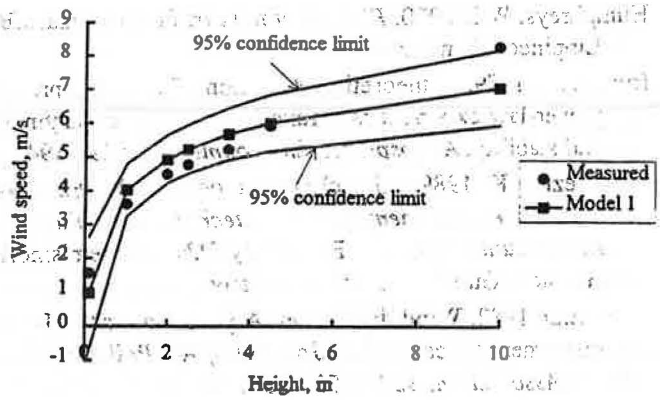

Figure 5 Ninety-five percent confidence and prediction bands of model 1 for data set 2.

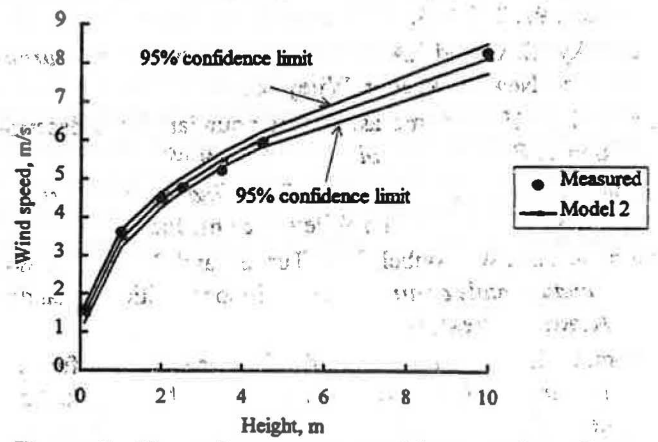

Figure 6 Ninety-five percent confidence and prediction bands of model 2 for data set 2.

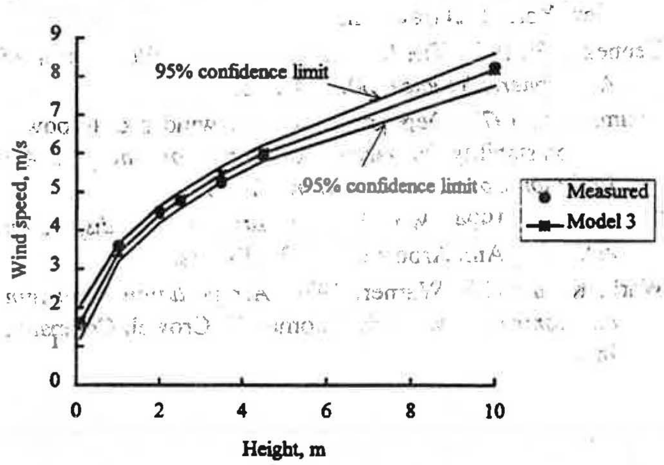

Figure 7 Ninety-five percent confidence and prediction bands of model 3 for data set 2.

predicted results. Figure 5 also confirms what was learned by the preceding criticism: that the logarithmic law may produce an unreal negative speed for $Z < 10$ m.

The results obtained here were based on a limited number of measurements of wind speed vs. height. More research and measurements are necessary regarding the variability of the parameters in the models with various locations or atmospheric stability classes. In addition, several identical airspeed probes should be arranged so that simultaneous measurements of wind speed vs. height in the boundary layer can be made.

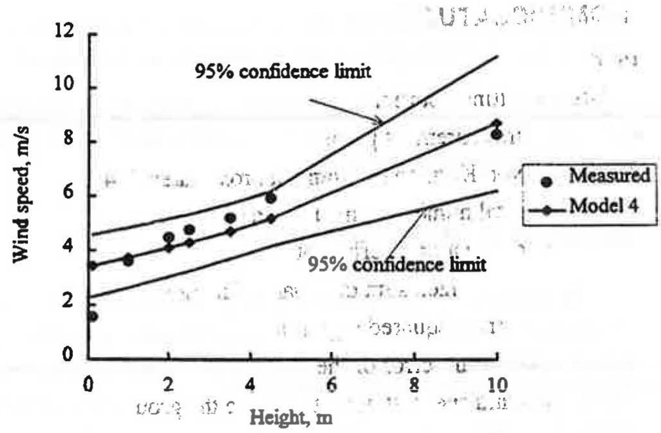

Figure 8 Ninety-five percent confidence and prediction bands of model 4 for data set 2.

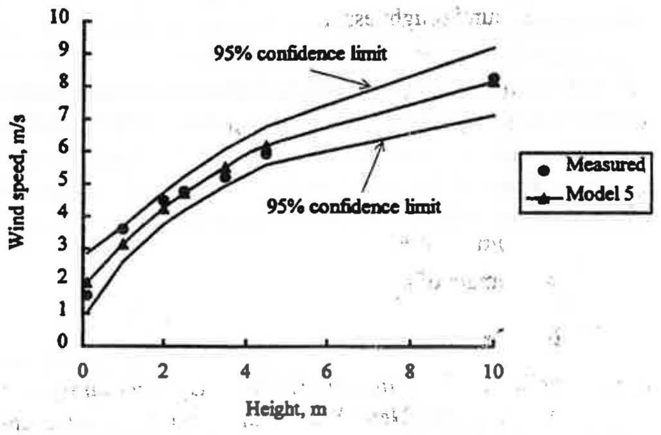

Figure 9 Ninety-five percent confidence and prediction bands of model 5 for data set 2.

CONCLUSIONS

The logarithmic model did not adequately describe the variation of wind speed with height between 0 m and 10 m above the ground.

The power law models were found to be more applicable. The exponential term was in the range of 0.3 to 0.6 for the two-parameter model and 0.4 to 0.6 for the three-parameter model. Besides the logarithmic and power law models, the three-parameter exponential function can favorably fit wind speed vs. height data.

Wind data measured by weather stations at a height of 10 m can be easily interpolated to any height between 0 m and 10 m using models with the estimated parameters in this research. More research and measurements are necessary regarding the variability of the parameters in the models with various locations and atmospheric stability classes.

NOMENCLATURE

b_1, b_2, and b_3	=	fitting coefficients
i	=	measurement point
k	=	von Karman constant, approximately 0.4
n	=	total number of measurements
R^2	=	correlation coefficient
S	=	minimized sum of squared function
SSR	=	sum of squared regression
SE	=	standard error of the fit
u	=	wind speed at height Z above the ground
u_*	=	shear velocity
u_{10}	=	wind speed at a height of 10 m above ground
X	=	sensitivity matrix
Z_0	=	ground roughness, m
Z	=	height above ground, m
ψ	=	estimate of u
τ_0	=	stress of wind at ground level
ρ	=	air density
β_1	=	estimate of b_1
β_2	=	estimate of b_2
β_3	=	estimate of b_3

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