

Characteristic Wind Speed Distributions and Reliability of the Logarithmic Wind Profile

K. S. Ro, P.E.¹; and P. G. Hunt²

Abstract: Wind produces turbulence facilitating the exchange of pollutants and other environmentally important trace gases such as oxygen and greenhouse gases between stationary water bodies and the atmosphere. Whereas wind speeds continuously vary, different wind speed monitoring and characterization procedures have been used for the gas exchange studies. We assessed the impact of measurement time intervals, logarithmic wind speed profiles, and surface roughness values on wind characterizations. The Weibull probability density function effectively characterized yearly and seasonal wind speed distributions. It was not affected by various averaging time intervals (1–60 min). However, averaging time interval of <10 min was necessary for reliable characterizations of shorter-periods (<3–5 days). Vertical wind speed variations were effectively described by logarithmic profile irrespective of atmospheric stability conditions. Interestingly, use of the logarithmic profile allowed the actual U_{10} to be predicted with reasonable accuracy for a wide range of surface roughness values. This was true under all stability conditions. Thus, small time intervals and the logarithmic profile appear to be very robust and widely useful techniques.

DOI: 10.1061/(ASCE)0733-9372(2007)133:3(313)

CE Database subject headings: Wind speed; Surface roughness; Pollution.

Introduction

Wind plays a very important role in transporting dusts, odors, and pollutants from one location to another. It also produces turbulence in stationary water bodies such as lakes and lagoons. This wind-driven turbulence facilitates the exchanges of heat, momentum, and mass of environmentally important gases such as oxygen, volatile organic compounds, ammonia, etc. between the water bodies and the atmosphere. Wind is one of the dominant factors influencing the extents of emission and dispersion of ammonia and other odorous compounds from concentrated animal feeding operations, which have become a major concern for farmers, industry, and regulatory agencies. In addition, wind-driven oxygen transfer into standing water bodies plays an important role in lake water quality and efficacy of lagoon systems for treating wastewater.

Despite the importance of wind speed in many environmental gas transfer processes, characterizing continuously varying wind speed is not a simple task. Wind in the field continuously changes both speed and direction. Further, there is a lack of standards for characterizing the impact of variable wind speed on gas transfer. Characteristic wind speeds have been frequently represented by

simple average wind speeds. Unfortunately, a simple arithmetic average wind speed will not adequately characterize the actual nonlinearity of wind-driven gas transfers. As an example, wind energy depends on the cube of wind speed. Thus, the characteristic wind speed providing a snap shot of a site's energy density would be better represented by the root-mean-cubed wind speed, not the arithmetic mean wind speed.

In addition to the lack of wind speed characterization procedures, there is no clear guidance given for what averaging time intervals should be used for the anemometric wind speed measurements. The ASAE standards for measuring drift deposits from ground, orchard, and aerial sprayers (ASAE 2005) recommends measuring time-averaged wind speed for 2 min or more with sampling frequency not less than four samples per minute. However, hourly average values of wind speed and direction are required for the USEPA AERMOD dispersion model. The USEPA model recommends sampling frequency of every 1–5 s when averaging wind speed and direction (USEPA 2000). Other researchers involved in gas transfer studies used averaging times of 1 min (Wanninkhof et al. 1984), 4 min (Upstill-Goddard et al. 1990), and 15 min (Harper et al. 2000). The effect of using different averaging times on gas transfer has not been reported.

Another ambiguous wind speed measurement procedure is the use of the logarithmic wind profile relationship to relate wind speed at one height to another by taking the ratios. Wind speed at 10 m height has been used as a reference wind speed in the field, but wind speeds at lower heights are more conveniently measured. To relate the two wind speeds, researchers frequently use the logarithmic profile to relate the two wind speeds without checking its underlying assumption of neutrally stratified atmosphere (Upstill-Goddard et al. 1990; Yu et al. 1983). The logarithmic wind profile under a neutrally stratified atmospheric condition is

$$U_z = \frac{u_{*a}}{k} \ln\left(\frac{z}{z_0}\right) \quad (1)$$

¹Environmental Engineer, USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, 2611 West Lucas St., Florence, SC 29501-1241 (corresponding author). E-mail: kyoungflorence.ars.usda.gov

²Soil Scientist/Research Leader, USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, Florence, SC 29501-1241.

Note. Discussion open until August 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on December 28, 2005; approved on October 1, 2006. This paper is part of the *Journal of Environmental Engineering*, Vol. 133, No. 3, March 1, 2007. ©ASCE, ISSN 0733-9372/2007/3-313-318/\$25.00.

The surface roughness parameter (z_0) of Eq. (1) defines the effectiveness of a canopy for absorbing momentum, or the height where the extrapolated wind speed approaches zero. Typical values of z_0 for different terrains can be readily found from the literature (Arya 2001; Sutton 1953). If the wind speed at one height and the value of z_0 for the terrain of interest are known, the wind speed at 10 m height can be computed by taking ratios, thereby eliminating the need to assess the friction velocity:

$$\frac{U_{10}}{U_z} = \ln\left(\frac{10}{z_0}\right) / \ln\left(\frac{z}{z_0}\right) \quad (2)$$

Wind speed often occurs under nonneutrally stratified conditions, and the validity of Eq. (2) is not known when conditions are nonneutrally stratified. In addition, the accuracy of Eq. (2) in predicting the 10-m wind speed with broadly defined values of z_0 for a given terrain needs to be examined for its broader functionality.

The objectives of this investigation were to assess (1) the impact of measurement time interval on the efficacy of the Weibull probability density function for wind speed characterization; and (2) the reliability of the logarithmic profile for predicting vertical wind profiles and estimating the 10-m wind speed with a wide range of surface roughness values.

Materials and Methods

Wind Speed Measurements

A micrometeorological station was constructed on the grass plain of the Coastal Research Center at Florence, SC (N 34° 14.741' and W 79° 48.605'). The immediate vicinity of the station was covered with short grass (typically less than 0.1 m). Approximately 60 m south of the station, soybeans, wheat, and peanuts (maximum heights less than 0.7 m) were planted under two center pivot irrigation systems (270 m in diameter). A few buildings (about 10 m in height) were located 110 m north of the station. The predominant wind direction was NE-SW, which was along the length of the grass plain (approximately 700 m in length). The weather station was equipped with one, two-dimensional and six, cup anemometers; a data logger; and sensors for both relative humidity and temperature (CS800-L Climatronics Wind Set, Vaisala Temperature/RH Probes, CR23X Micrologger, Campbell Scientific, Logan, Utah).

Whereas the 10-m mast was not constructed until September 2005, wind speed and direction, temperature, and relative humidity were measured at six heights (0.5, 1.7, 2.1, 2.7, 3.7, and 4.3 m) from January to September 2005. The 10-m mast was erected in September 2005, and these parameters were measured at seven heights (0.7, 1.5, 2.6, 4.3, 6.0, 8.2, and 10.0 m) through December 2005.

The characteristic wind speed (U_{10}) distributions for 2005 were determined at 1, 5, 10, 15, 20, 30, and 60 min averaging time intervals based on (1) U_{10} estimated from the wind speeds measured at six heights up to 4.3 m from January to September 2005, and (2) U_{10} directly measured 10 m for the remainder of 2005. This procedure produced a large number of linearly logarithmic, six-point regression curves for wind speed versus height. Moreover, the coefficient of determination (R^2) was greater than 0.8 for approximately 81–92% of the entire 2005 data sets depending on averaging time scales.

The reliability of the logarithmic profile for predicting vertical wind profiles and estimating the 10-m wind speed was evaluated

based on the data sets with the 10-m measurements (i.e., from September 2005 to April 2006). The sampling rate of the anemometers was every 5 s and the wind speeds were averaged for periods of 1 min by the data logger. The 1-min wind speed raw data were later averaged for 5, 10, 15, 20, 30, and 60 min.

Weibull Distribution for Wind Speed

The two-parameter Weibull distribution is frequently used to model varying wind speeds (Davenport 1967; Hennessey 1977; Livingstone and Imboden 1993; Pavia and O'Brien 1986; Van der Anwara et al. 1980). The Weibull distribution is more flexible and also yields lower errors than the log-normal distribution for this purpose (Luna and Church 1974; Justus et al. 1976). The two-parameter Weibull probability density function $f(U_{10})$ is given by

$$f(U_{10}) = \frac{\beta}{\lambda} \left(\frac{U_{10}}{\lambda}\right)^{\beta-1} \exp\left[-\left(\frac{U_{10}}{\lambda}\right)^\beta\right] \quad \text{for } U_{10} > 0, \text{ otherwise } f(U_{10}) = 0 \quad (3)$$

The mean and the variance associated with the Weibull distribution are

$$E(U_{10}) = \lambda \Gamma\left(1 + \frac{1}{\beta}\right) \quad (4)$$

$$\text{Var}[U_{10}] = \lambda^2 \left[\Gamma\left(1 + \frac{2}{\beta}\right) - \left(\Gamma\left(1 + \frac{1}{\beta}\right)\right)^2 \right]$$

where

$$\Gamma(r) = \int_0^{\infty} t^{r-1} e^{-t} dt = \begin{cases} \text{gamma function} & \text{for } r > 0 \\ 0 & \text{otherwise} \end{cases}$$

Nonlinear regression subroutines of the SAS (Version 9.00, SAS Institute Inc., Cary, N.C.) and Geopad Prism (Version 4.03, GraphPad Software, Inc., San Diego) were used to estimate these two parameters (β and λ) based on our wind speed data.

Results and Discussion

Wind Speed Distribution

The Weibull distributions of the 10-m wind speeds (5-min average) for the Year 2005 fitted very well with $R^2=0.99$ (Fig. 1). For the entire data set, the wind speed could be characterized with the Weibull distribution with $\beta=1.9$ and $\lambda=2.8$. The mean wind speed and the variance were 2.5 m/s and 1.9 m²/s², respectively. Our β value of 1.9 is very similar to that reported by Troen and Peterson (1989), who showed that the values of β were close to 2 for the fitted Weibull distributions of wind speeds in northern Europe. Fig. 1 also shows that the overall wind speed distribution is composed of two underlying distributions of wind speed for daytime (from 6:00 a.m. to 6:00 p.m.) and for nighttime (from 6:00 p.m. to 6:00 a.m.). As expected, the daytime mean wind speed for the Year 2005 (2.8 m/s) was stronger than that of the nighttime (2.0 m/s).

The wind speed statistics were also analyzed for seasonal variation (Fig. 2). The mean wind speeds of winter (2.8 m/s for January, February, and December 2005) and spring (2.8 m/s for March, April, and May 2005) were higher than that for summer (2.0 m/s for June, July, and August 2005) and fall (2.4 m/s for September, October, and November 2005).

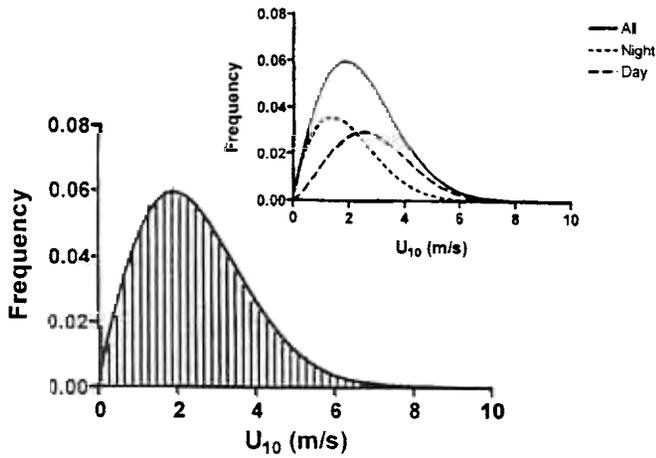


Fig. 1. Weibull distribution of wind speed for Year 2005 [$\beta=1.9$, $\gamma=2.8$, $R^2=0.99$, and $E(U_{10})=2.5$ m/s]

Effects of Different Averaging Times for Wind Speed Distributions

The effects of different averaging time intervals on the Weibull distribution were compared with the 10-m wind speed data collected for the entire Year 2005 and for three days during a gas transfer study in October 2005. For the yearly and seasonal wind speed distributions, averaging time did not significantly influence the shape of the distributions, or the coefficients of determination. It appears that the Weibull distribution was very robust relative to averaging time. No matter which averaging time was used, the same values of the two Weibull distribution parameters (i.e., β and λ) were obtained, and the curve fits were quite similar. Thus, when data for long periods are available, the averaging time is of little consequence.

However, over a shorter study period, averaging time strongly influenced the coefficient of determination for the wind speeds

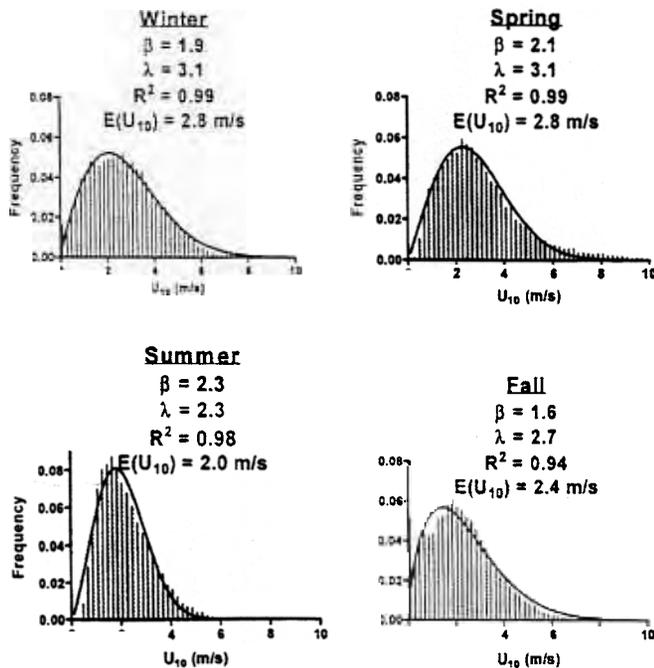


Fig. 2. Seasonal variation of wind speed distribution

Table 1. Values of Weibull Parameters for Long- and Short-Study Periods

Averaging time intervals (min)	Year 2005			October 24–26, 2005		
	β	λ	R^2	β	λ	R^2
5						
10						
15						
20						
30						
60						

collected. For the three days in October, 2005, the coefficients of determination decreased rapidly with the increase in averaging time intervals beyond 10 min (Table 1 and Fig. 3). Similar trends were observed throughout the Year 2005 for shorter gas transfer study periods (3–5 days). Therefore, averaging time less than 10 min is preferable for characterizing wind speed variation with the Weibull distribution for short study periods.

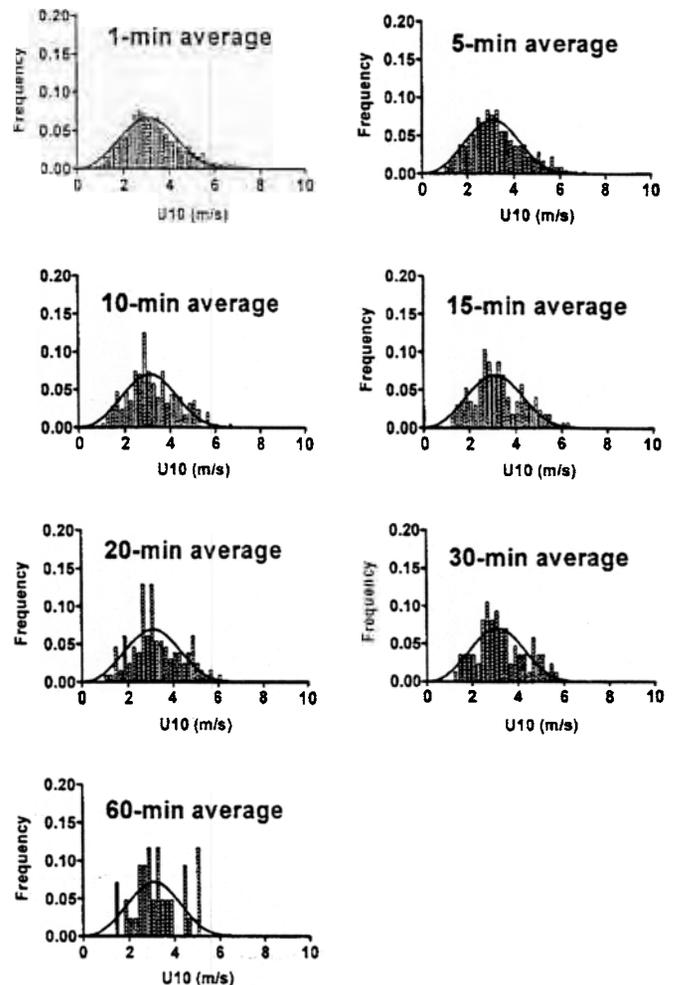


Fig. 3. U_{10} distribution during October 24–26, 2005

Table 2. Stability Conditions for the 5-Min Wind Speed Data Sets

SR	Atmospheric stability	% Occurrence		
		Entire data sets	Data sets with $R^2 > 0.9$	Data sets with $R^2 > 0.8$
<-1.7	Very unstable	3.0	1.3	1.9
From -1.7 to -0.1	Unstable	25.5	28.2	26.5
From -0.1 to 0.1	Neutral	21.0	24.0	22.5
From 0.1 to 1.2	Stable	30.4	33.0	32.2
1.2 to 4.9	Very stable	12.9	11.2	13.0
>4.9	Extremely stable	7.2	2.3	3.9

Reliability of the Logarithmic Profile

Logarithmic Fit of Vertical Wind Speeds

It is well known that the horizontal wind speed varies logarithmically with height under a neutrally stratified atmospheric condition [Eq. (1)], a condition in which an air parcel has a temperature equal to that of its surroundings and experiences zero buoyant force (Munn 1966; Arya 2001). Unfortunately, the atmosphere seldom achieves the strictly neutral condition. In order to test the applicability of Eq. (2) under all atmospheric stability conditions, 5-min average wind speeds collected at four different heights were fitted to a linearized logarithmic profile:

$$U_z = a \ln z + b \tag{6}$$

These data were collected from September 16, 2005 to April 27, 2006. This provided 53,051 four-point data sets that were fitted to the linearized logarithmic (LL) profile. Among the 53,051 LL regression lines, 78.7% had $R^2 > 0.9$. Further, 93.1% of the LL regression lines had $R^2 > 0.8$. Thus, nearly all of the wind speed data sets collected during the test period were well fitted to the logarithmic profile, irrespective of atmospheric stability conditions.

Stability Classes of the 53,031 Data Sets

In order to characterize the atmospheric stability conditions associated with the 53,051 data sets, stability ratios were determined. The stability ratio (the following equation) is a simplified approximation of the Richardson number, which has long been used as a dynamic stability parameter (Fritz 2003; Munn 1966; Yates et al. 1966, 1974):

$$SR = \frac{T_{z1} - T_{z2}}{\bar{U}^2} \times 10^5 \tag{7}$$

The four separate stability classes based on the stability ratio as suggested by Yates et al. (1974) are shown in Table 2. The atmospheric conditions with the stability ratios <-1.7 or >4.9 were not previously defined by Yates et al. (1974), but occurred in our data. These extreme values represent conditions 10.2% of the entire 5-min data sets. In this 10.2%, 3% of the data sets occurred under $SR < -1.7$, and 7.2% of the data sets occurred under $SR > 4.9$. We arbitrarily defined two additional atmospheric stability classes as (1) very unstable for $SR < -1.7$; and (2) extremely stable for $SR > 4.9$.

It is remarkable that 93.1% of the entire 53,051 LL regression lines were fitted reasonably well to Eq. (6) with $R^2 > 0.8$ regardless of the atmospheric stability conditions: Only 21% of the LL regression lines were collected under near neutrally stratified con-

ditions. This indicated that the neutrally stratified atmospheric condition was not necessary for good logarithmic fits.

It also supports the more generalized logarithmic velocity profile as first suggested by Monin and Obukhov (1954) and later modified to more convenient forms (Arya 2001)

$$\frac{\partial U}{\partial z} = \frac{u_*^* \phi_m(\zeta)}{kz} \tag{8}$$

Under the neutrally stratified condition, ϕ_m of Eq. (8) is unity, and the resulting equation becomes the familiar logarithmic velocity profile [Eq. (1)]. However, for nonneutral conditions, the value of ϕ_m strongly depends on the Monin-Obukhov length (L), which can be interpreted as a characteristic height below which the wind shear-generated turbulence dominates over the buoyancy effects. For instance, under stable atmospheric conditions, the momentum stability function can be estimated as a linear function of the stability parameter (Businger et al. 1971)

$$\phi_m = 1 + 4.7\zeta \quad \text{for } \zeta \geq 0 \text{ (stable)} \tag{9}$$

Integrating Eqs. (8) and (9) under stable atmospheric conditions, the wind speed profile becomes

$$U_z = \frac{u_*^*}{k} \left[\ln \frac{z}{z_0} + \frac{4.7(z - z_0)}{L} \right] \tag{10}$$

Eq. (10) suggests that wind speed should also be fitted well with logarithmic heights even under the stable (i.e., nonneutral) conditions, as did our data.

Surface Roughness Lengths

If the data sets were taken under neutrally stratified condition, surface roughness parameter values could be estimated from the LL regression line slopes and intercepts [i.e., a and b of Eq. (6)]. Comparing with Eq. (1), a and b of the LL regression line should be u_*^*/k and $-u_*^*/k \ln z_0$, respectively. However, Eq. (10) clearly shows that the values of z_0 estimated from Eq. (6) with a convenient assumption of neutral stability may produce erroneous results despite the good logarithmic fit of the wind speed. Only those z_0 values estimated from the wind speed data sets under neutral conditions are meaningful.

Albeit not meaningful under nonneutrally stratified atmospheric conditions, the values of z_0 were determined from the slopes and the intercepts of the LL regression lines as if all data sets with $R^2 > 0.9$ (i.e., 78.7% of the 53,051 data sets) were collected under neutrally stratified condition (Table 3). In general, the log fits of wind speed data under stable conditions yielded overestimates of z_0 ; whereas, the wind speed data under unstable conditions yielded slightly underestimates of z_0 . The z_0 values estimated from the wind speed under the two highest stability ratios (i.e., very stable to extremely stable stability classes) were an order of magnitude higher than those z_0 values estimated under theoretically valid neutrally stratified condition.

The average values of z_0 under the neutrally stratified condition were 5 mm using the 5–60 min average wind speeds. However, 1-min wind speed data set yielded slightly higher value of z_0 (7 mm) with a much larger standard deviation (14 mm). The mean value of z_0 for various averaging time intervals under the neutrally stratified condition was 5.3 mm. This average roughness length of 5.3 mm was close to the values of z_0 for grass plains (i.e., 6–20 mm) according to the z_0 table of Arya (2001).

Table 3. Surface Roughness Lengths Predicted from Various Time-Averaged Wind Speeds and Stability Conditions (Data Sets with $R^2 > 0.9$)

Atmospheric stability	Apparent z_0^a (mm)						
	1 min	5 min	10 min	15 min	20 min	30 min	60 min
Very unstable	10±24	2±8	2±5	1±4			
Unstable	7±14	5±8	4±7	4±7			
Neutral	7±12	5±8	5±7	5±7			
Stable	21±29	15±19	15±18	14±17			
Very stable	81±74	72±60	68±55	68±54			
Extremely stable	119±105	108±98	94±92	85±87			

^aThose z_0 values of nonneutral conditions are not valid surface roughness factors as defined by Eq. (1).

Estimation of the 10-m Wind Speed with a Wide Range of z_0 Values

The fact that a wide range of z_0 values (1–119 mm) were produced from the good logarithmic fit of the wind speed under all stability conditions infers that accurate estimation of z_0 may not be critical in estimating U_{10} using Eq. (2). This can be good news for researchers who predict U_{10} from the wind speed conveniently measured at lower heights using Eq. (2) with a literature value of z_0 loosely classified by terrain characteristics. For instance, our study site may be characterized as a mixture of grass plain and farmland with uncut grass with isolated trees. The corresponding literature z_0 values range from 6 to 30 mm (Arya 2001). In order to test how accurately we could predict U_{10} with the literature values of z_0 , three values of z_0 , 6, 20, and 100 mm were selected. The selection of these z_0 values reflects the lowest value of ($z_0 = 6$ mm) the “fairly level grass plains,” the transition from fairly level grass plains ($z_0 = 20$ mm) to the upper limit ($z_0 = 100$ mm) of “farmland with many hedges” (Arya 2001). Each of the entire wind speed data sets (i.e., 53,051 data sets) measured at five different heights (0.7, 1.5, 2.6, 4.3, and 6.0 m) was used with each of the three z_0 values in order to predict U_{10} according to Eq. (2). These predicted U_{10} were compared with the measured U_{10} by taking the ratios (Fig. 4).

As shown in Fig. 4, most distributions of the ratio (predicted U_{10} over measured U_{10}) were slightly right skewed, but mostly clustered around unity with narrow standard deviations. Except for the predictions based on $z_0 = 100$ mm and the wind speed measured at 0.7 m, the majority of the logarithmic profile procedures predicted U_{10} with average values of the ratio (predicted U_{10} over measured U_{10}) within 1 ± 0.05 regardless of the underlying atmospheric stability conditions. The logarithmic profile procedures with the wind speed measured at higher heights (i.e., near 10 m) yielded better prediction with smaller deviations. With the wind speed measured at or above 2.6 m, all three values of z_0 (i.e., 6, 20, and 100 mm) predicted U_{10} reasonably well. However, the wind speed measured at heights lower than 2.6 m did not predict U_{10} well when $z_0 = 100$ mm was used (about 20 times more than measured z_0 value).

Conclusions

Results from this study showed that the Weibull probability distribution function can be successfully used to describe highly variable wind speeds in the field. The values of the Weibull parameters for the Year 2005 wind speed statistics at our test site were $\beta = 1.9$ and $\lambda = 2.8$ with $R^2 = 0.99$. Similar analysis were performed to estimate the Weibull parameters for wind speed statistics for day and night time, winter, spring, summer, and fall seasons.

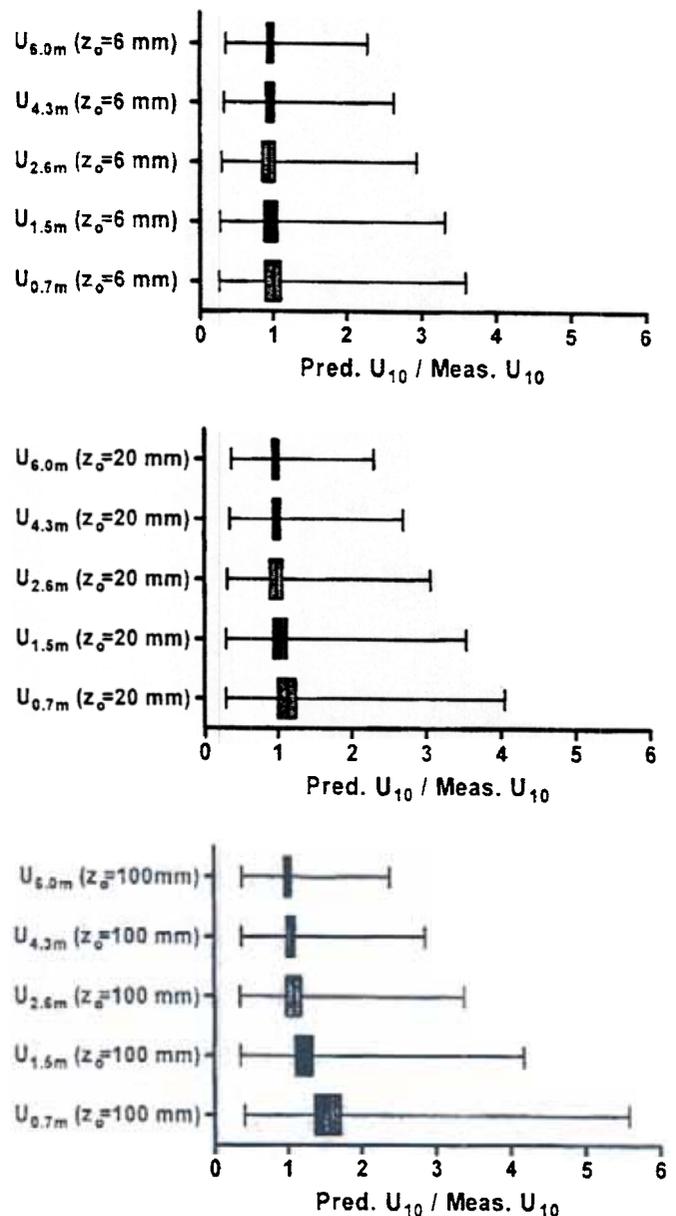


Fig. 4. Ratios of predicted U_{10} /measured U_{10}

There were no significant effects of wind speed averaging time on the Weibull distribution for wind speed data sets collected over long study periods. However, for shorter study periods (less than 5 days), wind speeds averaged beyond 10 min did not satisfactorily fit to the Weibull distribution. Yet the coefficients were surprisingly robust, despite the reduction in fit with longer averaging intervals. Most of the wind speeds were fitted nicely to the LL profile under all atmospheric stability conditions as suggested by the generalized logarithmic velocity profiles.

The majority of the logarithmic profile procedures predicted U_{10} rather well regardless of the underlying atmospheric stability conditions. Further, use of accurate values of z_0 appeared not to be critical in estimating U_{10} with reasonable accuracy. Therefore, one can use Eq. (2) for estimating U_{10} irrespective of the atmospheric stability conditions. This is an extremely useful and widely applicable finding. However, for it to be confidently used, the finding of this paper needs to be reproduced under a wide region of climate and geographic conditions.

Acknowledgments

The writers are indebted to Mr. M. Johnson for the collection, organization, transformation, and analysis of a large volume of data.

Notation

The following symbols are used in this paper:

- a, b = arbitrary constants;
- C_p = heat capacity (J/kg/K);
- g = gravitational acceleration (m/s²);
- k = von Karman's constant (=approximately 0.4)
- $L = -u_a^{*3} T_p C_p / g k Q_H$
= Monin-Obukhov length (m);
- Q_H = heat flux (J/m²/s);
- SR = stability ratio;
- T = temperature (K);
- T_{z1}, T_{z2} = air temperatures (°C) at heights 10 and 2.6 m;
- \bar{U} = wind speed measured at a height equidistant from 10 and 2.6 m (m/s);
- U_z = wind speed at height z (m/s);
- U_{10} = wind speed at 10 m height (m/s);
- $u_{*,a}$ = air friction velocity (m/s);
- z = height from the ground (m);
- z_0 = surface roughness parameter, or the height at which U profile extrapolates to 0 (m);
- β = shape parameter;
- $\zeta = z/L$ = stability parameter;
- λ = scaling factor;
- ρ = density (kg/m³); and
- ϕ_m = momentum similarity function.

References

- American Society of Agricultural Engineers (ASAE). (2005). "Procedure for measuring drift deposits from ground, orchard, and aerial sprayers." *S561.1 APR2004*. ASABE, St. Joseph, Mich.
- Arya, S. P. (2001). *Introduction to micrometeorology*, Academic, New York.
- Businger, J. A., Wyngaard, J. C., Izumi, Y., and Bradley, E. F. (1971). "Flux-profile relationships in the atmospheric surface layer." *J. Atmos. Sci.*, 28(2), 181–189.
- Davenport, A. G. (1967). "The dependence of wind loads on meteorological parameters." *Proc., Int. Research Seminar on Wind Effects on Buildings and Structures*, National Science Foundation, Ottawa, 19–82.
- Fritz, B. K. (2003). "Measurement and analysis of atmospheric stability in two Texas regions." *ASAE AA03-005*, St. Joseph, Mich.
- Harper, L. A., Sharpe, R. R., and Parkin, P. B. (2000). "Gaseous nitrogen emissions from anaerobic swine lagoons: Ammonia, nitrous oxide, and dinitrogen gas." *J. Environ. Qual.*, 29, 1356–1365.
- Hennessey, J. P., Jr. (1977). "Some aspects of wind power statistics." *J. Appl. Meteorol.*, 16(2), 119–128.
- Justus, C. G., Hargraves, W. R., and Yalcin, A. (1976). "Nationwide assessment of potential output from wind powered generators." *J. Appl. Meteorol.*, 15(7), 673–678.
- Livingstone, D. M., and Imboden, D. M. (1993). "The non-linear influence of wind-speed variability on gas transfer in lakes." *Tellus, Ser. B*, 45B(3), 275–295.
- Luna, R. E., and Church, H. W. (1974). "Estimation of long-term concentrations using a universal wind speed distribution." *J. Appl. Meteorol.*, 13(8), 910–916.
- Monin, A. S., and Obukhov, A. M. (1954). "Basic laws of turbulent mixing in the ground layer of the atmosphere." *Geophys. Inst., Acad. Sci., U.S.S.R.* 24(151), 163–187.
- Munn, R. E. (1966). *Descriptive meteorology—Advances in geophysics supplement 1*, Academic, New York.
- Pavia, E. G., and O'Brien, J. J. (1986). "Weibull statistics of wind speed over the ocean." *J. Clim. Appl. Meteorol.*, 25(10), 1324–1332.
- Sutton, O. G. (1953). *Micrometeorology*, McGraw-Hill, New York.
- Troen, I., and Peterson, E. L. (1989). *European wind atlas*, Commission of the European Communities Directorate-General for Science, Research and Development, Brussels, Belgium and Risø National Laboratory, Roskilde, Denmark.
- United States Environmental Protection Agency (USEPA). (2000). "Meteorological monitoring guidance for regulatory modeling applications." *EPA-454/R-99-005*, Washington, D.C.
- Upstill-Goddard, R. C., Watson, A. J., Liss, P. S., and Liddicoat, M. I. (1990). "Gas transfer velocities in lakes measured with SF₆." *Tellus, Ser. B*, 42B(4), 364–377.
- Van der Anwar L., De Meyer, F., and Malet, L. M. (1980). "The use of the Weibull three-parameter model for estimating mean wind power densities." *J. Am. Meteorol. Soc.*, 19(7), 819–825.
- Wanninkhof, R., Ledwell, J. R., and Broecker, W. S. (1984). "Gas exchange-wind speed relation measured with sulfur hexafluoride on a lake." *Science*, 227(4691), 1224–1226.
- Yates, W. E., Akesson, N. B., and Coutts, H. H. (1966). "Evaluation of drift residues from aerial applications." *Trans. ASAE*, 9(3), 389–393.
- Yates, W. E., Akesson, N. B., and Cowden, R. E. (1974). "Criteria for minimizing drift residues on crops downwind from aerial applications." *Trans. ASAE*, 17(4), 627–632.
- Yu, S. L., Hamrick, J. M., and Lee, D.-S. (1983). "Wind effects on air-water oxygen transfer in a lake." *Proc., Int. Symp. on Gas Transfer at Water Surfaces*, Cornell Univ., Ithaca, N.Y.