90-376-J

This article is reprinted from the TRANSACTIONS OF THE ASAE (Vol. 33, No. 6, pp. 1893-1899, 1990)
Published by the American Society of Agricultural Engineers, St. Joseph, MI 49085-9659 USA

STOCHASTIC WIND SIMULATION FOR EROSION MODELING

E. L. Skidmore, J. Tatarko

ABSTRACT

The purpose of this study was to develop a wind simulator to furnish wind direction and sub-hourly wind speed to users of wind speed information, particularly for wind erosion modeling. We analyzed the Wind Energy Resource Information System data to determine scale and shape parameters of the Weibull distribution for each of the 16 cardinal directions for each month at 704 locations in the United States. We also summarized wind direction distributions, ratio of daily maximum to daily minimum wind speed, and hour of maximum wind speed by month for each location. This summary of historical wind statistics constitutes a compact data base for wind simulation. Equations were formulated and procedures developed and used with the compact data base and a random number generator to simulate wind direction and sub-hourly wind speed. Cumulative wind speed distributions, calculated from the Weibull parameters, and wind speeds simulated at one-hour intervals for 1000 days agreed well. The model reflects historical day-to-day wind variation and wind speed variations within a day. It will be useful to those needing wind speed and wind direction information and will provide the wind simulator requirements in a wind erosion prediction system.

KEYWORDS. Erosion, Modeling, Wind simulation.

INTRODUCTION

The wind is of interest to many people. Wind energy developers, hydrologists, meteorologists, climatologists, farmers, ranchers, sportsmen, environmentalists, conservationists, agricultural pest managers, homemakers, and others all have reasons to know about the wind. This need for information about the wind has prompted several studies, particularly by those interested in wind as a source of energy (Hagen et al., 1980; Reed, 1975; Elliot et al., 1986) and those concerned with erosion of soil by wind (Lyles, 1976, 1983; Zingg, 1949; Skidmore, 1965, 1987).

Sometimes knowing wind speed without concern for wind direction is sufficient and, thus, many of the wind studies do not consider a wind direction component. But for application to wind erosion, wind direction is critical (Skidmore, 1987; Skidmore and Hagen, 1977; Skidmore and Woodruff, 1968). Wind direction relative to the orientation of fields and wind barriers is important in determining wind travel distance from a non-eroding boundary and enters into the estimation of wind erosion. Wind direction relative to the direction of row crops and some tillage operations also enters into the calculation, as does the constancy or preponderance of wind in the prevailing wind erosion direction. Both wind speed and wind direction are important in studies of evaporation from lakes and evapotranspiration from row crops.

Prediction of wind speed and direction, like most meteorological variables, is extremely difficult. Even with advanced technology, such as sophisticated numerical models and super computers, using climatological means is as accurate as predicting meteorological variables for a time period of more than a few days in advance (Tribbia and Anthes, 1987). Therefore, we resort to historical statistical information about most meteorological variables and use stochastic techniques to determine likelihood of various levels of the variable of concern.

Various models have been used to describe wind speed distribution. A glance at a frequency versus wind speed histogram shows that the distribution would not be described best by the familiar normal distribution. Distributions that have been used to describe wind speed include the one-parameter Rayleigh (Hennessey, 1977; Corotis et al., 1978), the two-parameter gamma (Nicks and Lane, 1989), and the two-parameter Weibull (Takle and Brown, 1978; Corotis et al., 1978). The Weibull is undoubtedly the most widely used model of common wind behavior representing wind speed distributions.

McWilliams et al. (1979) presented a model for the joint distribution of wind speed and direction. They assumed that the components of wind speed are normally distributed along any given direction and that a component along the favored direction has a nonzero mean and a given variance; whereas a component along a direction at right angles is independent and normally distributed with zero mean and the same variance.

Dixon and Swift (1984) expanded upon the work of McWilliams et al. (1979), and McWilliams and Sprevak (1980) by proposing an empirical three-parameter model. Two of these are the familiar Weibull characteristic scale and shape factors. The third is a measure of directionality, which is a function of the ratio of probability densities for prevailing/antiprevailing directions.

These various models are not adequate for wind erosion modeling, which requires directional sub-hourly wind speeds. Thus, the specific purpose of this study was to develop a more detailed stochastic wind simulator to

---

Article was submitted for publication in June 1990; reviewed and approved for publication by the Soil and Water Div. of ASAE in October 1990.

Contribution from USDA-ARS in cooperation with Kansas Agricultural Experiment Station. Contribution No. 90-376-J.

The authors are **E. L. Skidmore**, Soil Scientist, USDA-ARS, Kansas State University, and **J. Tatarko**, Research Assistant, Agronomy Dept., Kansas State University, Manhattan.

furnish wind direction and wind speed as needed by the Wind Erosion Prediction System described by Hagen (1990). A further requirement of the simulator is that it be capable of using the extensive wind data base summarized by the National Climatic Data Center.

COMPACT DATA BASE

One of the important requirements for a wind simulator for wind erosion modeling is to develop a compact data base. Although described elsewhere (Skidmore and Tatarko, 1990), we give here some of the details of creating the compact data base. Our database was created from historical monthly wind speed and wind direction summaries contained in the extensive Wind Energy Resource Information System (WERIS) data base at the National Climatic Data Center, Asheville, NC (NCC TD 9793). The WERIS data base is further described in appendix C of Elliot et al. (1986).

Data were extracted from WERIS tables and, in some cases, analyzed further to create a data base suitable for our needs. From WERIS Table 5, we obtained a ratio of maximum/minimum mean hourly wind speed and hour of maximum wind speed by month. From WERIS Table 10, we obtained monthly mean air density and occurrences of blowing dust. Air density is used to calculate wind power and wind shear stress. Although we are not using occurrence of blowing dust in our current modeling effort, we thought it important to archive in this data base for future studies.

We used data from WERIS Table 12 A-L, joint wind speed/direction frequency by month (Table 1), to calculate scale and shape parameters of the Weibull distribution function for each of the 16 cardinal wind directions by month.

The cumulative Weibull distribution function F(u) and the probability density function f(u) are defined by:

$$F(u) = 1 - \exp\left[-(u/c)^k\right] \tag{1}$$

and

$$f(u) = dF(u)/du = (k/c)(u/c)^{k-1}\exp\left[-(u/c)^k\right] \tag{2}$$

where

u = wind speed,

c = scale parameter (units of velocity), and

k = shape parameter (dimensionless) (Apt, 1976).

Since anemometer heights varied from location to location, all wind speeds (Column 1, Table 1) were adjusted to a 10 m reference height according to the following:

$$u_2 = u_1\left(z_2/z_1\right)^{1/7} \tag{3}$$

where

u_1 and u_2 = wind speeds at heights z_1 and z_2, respectively (Elliot, 1979).

The calm periods were eliminated, and the frequency of wind in each speed group was normalized to give a total of 1.0 for each of the 16 cardinal directions. Thus,

$$F_1(u) = [(F(u) - F_0)/(1 - F_0)] = 1 - \exp\left[(u/c)^k\right] \tag{4}$$

were $F_1(u)$ is the cumulative distribution with the calm periods eliminated, and F_0 is the frequency of the calm periods. The scale and shape parameters were calculated by

TABLE 1. Joint wind speed/direction frequency, March, Lubbock, TX (Table 12c of WERIS)

	Wind Direction																	
Speed (m/sec)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	CALM	Total
Calm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	1.7
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.3	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.3	0.1	0.5	0.5	.6	0.4	0.5	0.2	0.0	4.1
3	0.7	0.3	0.5	0.4	0.9	0.4	0.6	0.5	0.9	0.4	1.1	1.1	10.5	0.8	0.7	0.3	0.0	11.1
4	1.0	0.6	0.8	0.4	1.1	0.9	1.0	0.8	1.9	0.6	0.8	1.2	1.6	1.2	0.7	0.5	0.0	15.1
5	0.9	0.6	0.8	0.5	0.9	0.9	1.0	1.3	2.1	0.9	1.2	1.2	1.6	0.5	0.4	0.5	0.0	15.4
6	0.7	0.7	0.6	0.4	0.6	0.5	0.9	0.6	1.6	1.0	1.1	1.2	0.7	0.6	0.3	0.5	0.0	12.2
7	1.0	0.6	0.6	0.4	0.2	0.5	0.4	0.5	1.6	1.0	1.4	0.8	0.7	0.5	0.3	0.2	0.0	10.0
8	1.0	0.6	0.8	0.2	0.5	0.3	0.6	0.3	1.4	1.2	1.0	0.6	0.7	0.4	0.4	0.2	0.0	10.1
9	0.8	0.4	0.6	0.2	0.3	0.1	0.2	0.4	1.0	0.8	0.7	0.6	0.6	0.4	0.2	0.3	0.0	7.6
10	0.3	0.4	0.2	0.2	0.1	0.0	0.1	0.2	0.8	0.4	0.2	0.3	0.4	0.3	0.1	0.1	0.0	4.3
11	0.3	0.4	0.1	0.1	0.0	0.0	0.1	0.1	0.5	0.2	0.3	0.3	0.5	0.1	0.1	0.1	0.0	3.1
12	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.2	0.4	0.1	0.1	0.0	0.0	1.6
13	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.2	0.1	0.3	0.2	0.1	0.1	0.0	1.3
14	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.1	0.1	0.0	0.0	0.7
15	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.5
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21 - 25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26 - 30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31 - 35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
36 - 40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41 - up	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	7.8	4.8	5.1	2.9	4.9	3.8	5.1	4.9	12.2	6.8	8.9	8.5	9.9	5.7	4.0	3.0	1.7	100.0
Avg. speed	6.9	7.0	6.1	6.0	5.1	5.2	5.5	5.9	6.2	6.7	6.4	6.2	6.4	6.2	5.6	6.3	0.0	6.1

the method of least squares applied to the cumulative distribution function, equation 4. Equation 4 was rewritten as:

$$1 - F_1(u) = \exp\left[-(u/c)^k\right] \qquad (5)$$

Then by taking the logarithm twice, this becomes:

$$\ln\left[-\ln\left(1 - F_1(u)\right)\right] = -k \ln c + k \ln u \qquad (6)$$

If we let $y = \ln[-\ln(1 - F1(u))]$, $a = -k \ln c$, $b = k$, and $x = \ln u$, equation 6 may be rewritten as:

$$y = a + bx \qquad (7)$$

$F_1(u)$ was calculated from information in tables like Table 1 for each wind speed group, to determine y and x in equation 7. This gave the information needed to use a standard method of least squares to determine the Weibull scale and shape parameters. To recover the real distribution, we can rewrite equation 4 as

$$F_1(u) = F_0 + (1 - F_0)\left\{1 - \exp\left[-(u/c)^k\right]\right\} \qquad (8)$$

Wind direction distribution was summarized by month from the "total" row in Table 1 for each location.

Other pertinent data, obtained from the Wind Energy Resource Atlas of the United States (Elliot et al., 1986), included latitude, longitude, city, state, location name, Weather Bureau Army Navy (WBAN) number, period of record, anemometer height, and number of observations per 24 h period.

We eliminated WERIS sites if they represented less than 5 years of data, the anemometer height was not known, or fewer than 12 observations were taken per day. Where more than one satisfactory observation site/period remained in a metropolis, we picked the site with the best combination of the following:

1. Maximum number of hours per day observations were taken;
2. Longest period of record;
3. One hourly versus three hourly observations; and
4. Best location of anemometer (ground mast > beacon tower > roof top > unknown location).

RESULTS AND DISCUSSION

Tables 2, 3, 4, and 5 give examples of wind information we compiled into a compact data base for the simulation model.

TABLE 2. Ratio of maximum to minimum hourly wind speed, hour of maximum wind speed, air density and occurrences of blowing dust, Lubbock, TX (Skidmore and Tatarko, 1990)

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Max/min	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.7	1.5	1.6	1.6	1.5
Hour max	15	12	15	15	18	18	18	15	15	15	12	15
Air den (kg/m^3)	1.14	1.13	1.11	1.09	1.07	1.06	1.05	1.06	1.07	1.09	1.12	1.13
Blow dust	43	56	122	119	41	28	3	3	1	4	25	49

The scale and shape parameters (Tables 4 and 5) are used in equations 1 and 2 to define the wind speed probability distribution functions and are, therefore, useful for describing the wind speed regime. Equation 2 can be used to calculate the probability of any specified wind speed. The integrated form of equation 1 can be used to calculate the probability of wind speeds being greater than, less than, or between specified values. The mean wind speed of the observation period from which the distribution parameters were calculated is very nearly 0.9 times the scale parameter (Johnson, 1978).

The following few paragraphs explain procedure to access the compact data base and simulate wind direction and wind speed.

DETERMINE WIND DIRECTION

This analysis for stochastic determination of wind direction and wind speed is applied to wind data as summarized by Tables 2, 3, 4, and 5. Specify the month by number (1 = January) and read the wind direction distribution array for the specified month. Calculate the cumulative wind direction distribution so that it ranges from 0 to 1.0. Draw a random number, RN, where $0 < RN < 1.0$ and compare it with the cumulative wind direction distribution. If the random number is equal to or less than the probability of the wind being from the north, then the simulated wind direction is north. If the random number is greater than the cumulative probability of the wind being from the north and equal to or less than the probability of the wind being from the north northeast, then the simulated wind direction is north northeast and so on. If the random number is greater than the cumulative probability of the wind being from all of the 16 cardinal directions, then the simulated wind is calm.

DETERMINE WIND SPEED

Once wind direction is simulated, access the data base to determine the Weibull scale, c, and shape, k, parameters for that direction and the month under consideration in preparation for the next step.

Rearrange equation 8 to make wind speed, **u**, the dependent variable:

$$u = c\left\{-\ln\left[1 - \left(F(u) - F_0\right)/\left(1 - F_0\right)\right]\right\}^{1/k} \qquad (9)$$

Draw a random number, $0.0 \leq RN \leq 1.0$, assign its value to $F(u)$, and compare it with the frequency of calm periods, F_0. If $F(u) \leq F_0$, then u is calm. In the rare case that $F(u) = 1.0$, the argument of ln in equation 9 is zero and does not compute. Therefore, if $F(u) > 0.999$, let $F(u) = 0.999$. Otherwise, calculate u from equation 9 for $F_0 \leq F(u) \leq$

TABLE 3. Wind direction distribution by month, Lubbock, TX (Skidmore and Tatarko, 1990)

Wind Direction	Month 1	2	3	4	5	6	7	8	9	10	11	12
	%											
1	8.2	9.7	7.8	5.5	5.3	3.1	2.3	2.9	5.9	6.3	8.8	9.0
2	5.0	4.9	4.8	3.6	3.7	2.2	1.5	2.6	4.8	5.0	4.4	4.8
3	5.0	5.9	5.1	4.1	4.1	3.2	3.9	4.2	6.3	5.3	4.8	4.7
4	3.8	4.2	2.9	4.5	4.8	4.1	3.8	4.7	4.9	4.1	3.1	3.1
5	4.0	4.3	4.9	5.3	5.9	5.0	5.9	6.7	6.3	4.3	4.4	2.2
6	3.1	3.8	3.8	4.7	6.6	6.1	5.7	6.3	5.7	3.0	3.2	1.9
7	3.3	3.8	5.1	6.5	10.5	10.0	9.7	9.7	7.5	4.2	3.4	2.1
8	2.9	3.3	4.9	4.9	8.3	9.5	11.6	14.9	13.6	9.0	5.4	3.7
9	9.8	8.7	12.2	16.4	16.4	26.8	27.4	24.1	18.6	19.7	11.7	9.4
10	6.0	5.7	6.8	6.5	6.9	9.2	8.8	7.2	7.9	9.6	7.5	7.4
11	9.6	8.5	8.9	7.7	7.3	5.9	5.9	5.1	6.2	8.2	9.9	10.1
12	9.6	9.3	8.5	7.9	4.7	3.4	2.4	2.8	3.5	6.0	9.0	9.8
13	12.3	10.8	9.9	6.7	5.1	3.3	2.0	1.7	3.5	6.1	9.0	11.8
14	6.3	6.2	5.7	4.6	3.0	1.5	1.0	1.1	1.7	3.2	5.1	7.7
15	4.7	4.9	4.0	3.4	2.6	1.6	0.8	1.1	2.0	3.0	4.3	5.3
16	3.8	3.4	3.0	3.0	1.8	1.1	0.6	1.1	2.1	2.9	3.0	4.0
17	2.7	2.7	1.7	1.4	1.8	1.5	3.1	5.0	4.0	3.6	4.8	4.3

The directions are clockwise starting with 1 = north. Direction 17 represents calm periods.

0.999 to determine a period simulated wind speed. If the period is one day, then u represents simulated daily mean wind speed.

Many applications require additional information about how the wind speed might vary within a period. Consider a diurnal variation. Read from the wind data base the ratio of maximum to minimum wind speed and the hour of maximum wind speed for the location and month under consideration. Calculate the maximum and minimum wind speed for the day based on the representative wind speed as calculated above and given the ratio of umax to umin:

$$\text{urep} = (\text{umax} + \text{umin}) / 2 \qquad (10)$$

$$\text{uratio} = \text{umax} / \text{umin} \qquad (11)$$

where urep is the daily mean representative wind speed as calculated from equation 9, uratio is the ratio of daily maximum, umax, to daily minimum, umin, wind speed. Solving equation 10 and 11 for umax and umin gives:

$$\text{umax} = 2 \text{ uratio urep} / (1 + \text{uratio}) \qquad (12)$$

$$\text{umin} = \text{umax} / \text{uratio} \qquad (13)$$

Therefore, wind speed for any hour of the day u(I) can be simulated from:

$$\text{u (I)} = \text{urep} + 0.5 \; (\text{umax} - \text{umin}) \cos\left[2\pi\, (24 - \text{hrmax} + \text{I}) / 24\right] \qquad (14)$$

where hrmax is the hour of the day when wind speed is

TABLE 4. Weibull scale parameters by month and direction. Wind speed was adjusted to a height of 10 meters, Lubbock, TX (Skidmore and Tatarko, 1990)

Wind Direction	Month 1	2	3	4	5	6	7	8	9	10	11	12
	m/s											
1	8.0	8.2	8.8	8.3	8.0	7.6	5.8	5.0	6.4	7.5	7.5	7.9
2	8.2	9.2	9.0	8.6	8.3	7.6	6.0	5.7	7.3	7.5	6.7	8.1
3	6.6	7.8	8.0	8.3	7.9	7.2	5.8	5.8	5.9	7.0	6.5	6.8
4	6.5	6.5	7.8	6.9	7.3	6.3	5.9	5.2	5.3	6.2	5.7	6.3
5	6.0	6.3	6.7	6.4	6.6	6.3	5.2	4.8	4.6	5.2	5.0	5.0
6	5.3	6.4	6.8	7.1	7.1	6.2	5.3	5.0	5.2	5.1	5.1	4.2
7	5.5	6.4	7.2	7.2	7.4	6.8	6.0	5.5	5.5	5.3	4.8	5.2
8	5.9	6.1	7.5	8.5	8.0	7.5	6.3	5.8	5.9	6.2	5.8	5.2
9	6.2	7.0	7.9	8.5	8.1	8.0	6.8	6.5	6.5	6.6	6.2	6.5
10	7.2	7.2	8.7	8.5	8.1	7.7	6.9	6.5	6.9	6.9	6.9	7.4
11	7.3	7.6	8.2	8.4	7.6	6.9	6.1	5.9	6.1	6.2	6.5	6.9
12	6.5	7.0	8.0	8.6	7.8	7.0	5.4	5.0	5.2	5.9	6.4	6.0
13	6.7	6.8	8.3	8.8	7.2	6.4	4.9	4.4	5.3	5.1	6.3	6.4
14	7.1	7.2	7.8	8.1	7.0	5.6	4.3	4.2	4.6	5.1	6.0	6.9
15	6.1	6.1	7.2	7.2	7.1	5.3	4.6	4.5	4.4	4.9	6.4	6.5
16	7.1	7.7	7.7	8.3	6.6	5.7	4.8	3.9	4.9	6.4	7.1	7.2
17	6.8	7.3	8.1	8.2	7.7	7.3	6.3	5.8	5.9	6.3	6.4	6.7

The directions are clockwise starting with 1 = north. Direction 17 is for total wind.

TABLE 5. Weibull shape parameters by month and direction, Lubbock, TX (Skidmore and Tatarko, 1990)

Wind Direction	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
	ms											
1	2.5	2.5	2.7	2.6	2.8	2.3	2.2	2.6	2.3	2.5	2.7	2.7
2	2.8	2.4	3.2	2.9	2.8	2.7	3.2	2.3	3.1	2.8	2.7	2.6
3	2.8	3.1	3.3	2.8	2.7	2.9	2.8	3.3	3.2	3.3	3.0	3.2
4	3.9	3.4	3.0	3.5	3.0	2.6	2.8	2.9	3.2	3.1	2.7	3.2
5	3.1	3.2	3.3	2.9	3.0	3.4	3.1	3.2	3.3	3.0	3.6	2.8
6	3.4	3.6	3.9	3.3	3.6	4.4	3.7	3.9	3.3	3.5	3.6	5.1
7	3.7	3.3	3.3	3.3	3.4	3.6	3.5	3.5	3.9	4.1	3.6	5.4
8	3.2	4.1	3.3	3.5	3.3	3.5	3.8	3.7	3.5	2.9	3.0	4.5
9	2.9	3.2	3.6	3.3	3.3	3.7	3.7	3.7	3.4	3.3	3.3	3.2
10	3.1	3.5	3.7	3.7	3.2	3.5	3.9	3.6	4.0	3.2	3.5	3.2
11	3.4	3.2	2.7	3.2	3.2	3.0	3.5	3.0	3.4	3.0	3.2	3.2
12	2.5	2.6	2.5	2.4	2.5	2.9	3.4	3.6	3.0	2.7	2.6	2.6
13	2.1	2.4	2.2	2.5	2.6	2.2	3.3	3.1	3.0	2.4	2.2	2.2
14	2.1	2.2	2.3	2.5	2.4	3.6	4.1	3.5	2.6	2.4	1.8	2.0
15	2.4	2.6	2.2	2.5	2.5	3.1	3.3	2.9	2.9	2.0	2.2	2.3
16	2.2	2.6	2.7	2.3	2.8	3.3	2.6	3.5	2.5	2.1	2.4	2.4
17	2.6	2.6	2.7	2.9	3.1	3.1	3.3	3.2	3.0	2.7	2.6	2.6

The directions are clockwise starting with 1 = north. Direction 17 is for total wind.

maximum; I is index for hour of day, and the other variables are as previously defined.

OUTPUT FILE

Usually, the output of a wind simulation will be directed to the input of another process model, e.g., evaporation, wind energy, wind erosion, etc. We illustrate what the output of a few simulations may be like in Table 6. These simulations were generated by accessing data from Tables 2, 3, 4, and 5 for March and July and performing the operations described previously. After wind direction was determined based on wind direction probabilities, Table 3, and a random number generator, the appropriate Weibull scale and shape parameters were obtained from Tables 4 and 5. The model was run to produce the output shown in Table 6. Wind speed was printed every 2 h for each simulation.

If wind speed at any time exceeded 8 m/s, then it was flagged by a yes in the last column of Table 6. This means that wind speed is high enough to cause erosion from an unprotected surface of highly erodible particles, and an erosion sub-model should be activated.

Since Weibull scale factors describing wind speed distribution are indicative of higher wind speed in March than July, yes would appear more frequently, on the average for March than July, as it does in our small sample. Also, on the average of many simulations, the wind direction in the first column, Table 6, would reflect the direction distributions of Table 3.

TABLE 6. Wind direction and wind speed simulation for March and July, Lubbock, TX

Wind Direction	Hour of Day												Erosion
	1	3	5	7	9	11	13	15	17	19	21	23	
March	m/s												
13	3.3	3.2	3.3	3.7	4.1	4.6	5.0	5.1	5.0	4.6	4.1	3.7	No
11	4.6	4.4	4.6	5.1	5.7	6.4	6.9	7.0	6.9	6.4	5.7	5.1	No
13	2.7	2.6	2.7	3.0	3.4	3.8	4.1	4.2	4.1	3.8	3.4	3.0	No
4	6.2	5.9	6.2	6.8	7.7	8.6	9.3	9.5	9.3	8.6	7.7	6.8	Yes
9	6.9	6.7	6.9	7.7	8.7	9.7	10.4	10.7	10.4	9.7	8.7	7.7	Yes
11	8.0	7.7	8.0	8.9	10.0	11.2	12.0	12.4	12.0	11.2	10.0	8.9	Yes
10	5.4	5.2	5.4	6.0	6.8	7.6	8.1	8.3	8.1	7.6	6.8	6.0	Yes
12	1.7	1.7	1.7	1.9	2.2	2.4	2.6	2.7	2.6	2.4	2.2	1.9	No
5	3.4	3.3	3.4	3.7	4.2	4.7	5.1	5.2	5.1	4.9	4.2	3.8	No
7	7.3	7.0	7.3	8.1	9.2	10.2	11.0	11.3	11.0	10.2	9.2	8.1	Yes
July													
5	2.4	2.1	2.0	2.0	2.1	2.4	2.7	2.9	3.1	3.1	2.9	2.7	No
9	7.2	6.4	6.0	6.0	6.4	7.2	8.1	8.9	9.4	9.4	8.9	8.1	Yes
9	4.6	4.1	3.8	3.8	4.1	4.6	5.2	5.7	6.0	6.0	5.7	5.2	No
9	8.0	7.2	6.7	6.7	7.2	8.0	9.1	10.0	10.5	10.5	10.0	9.1	Yes
6	5.7	5.1	4.7	4.7	5.1	5.7	6.4	7.0	7.4	7.4	7.0	6.4	No
10	8.2	7.3	6.8	6.8	7.3	8.2	9.2	10.2	10.7	10.7	10.2	9.2	Yes
7	3.6	3.2	2.9	2.9	3.2	3.6	4.0	4.4	4.6	4.6	4.4	4.0	No
9	5.0	4.5	4.1	4.1	4.5	5.0	5.7	6.2	6.5	6.5	6.2	5.7	No
12	3.0	2.6	2.5	2.5	2.6	3.0	3.3	3.7	3.9	3.9	3.7	3.3	No
9	5.6	4.9	4.6	4.6	4.9	5.6	6.3	6.9	7.2	7.2	6.9	6.3	No

Directions are clockwise starting with 1 = north.

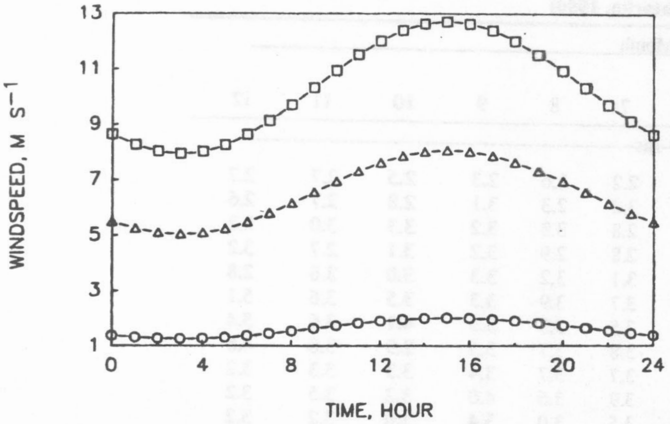

Figure 1–Hourly and daily variations of wind speed. The top and bottom curves are the highest and lowest, respectively, of a 10-day simulation. The middle curve is the average of 100 simulations, March, Lubbock, TX.

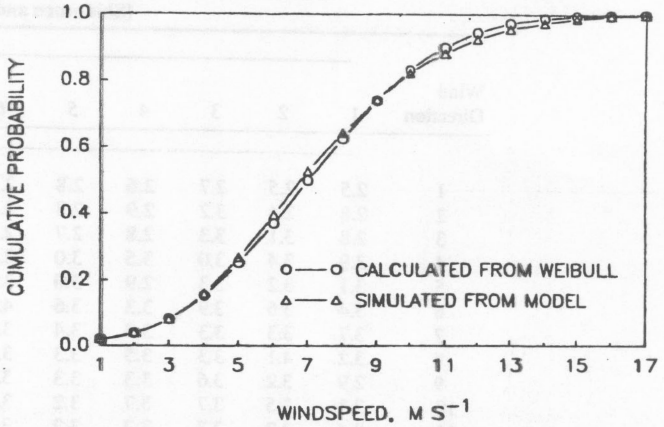

Figure 3–Simulated hourly wind speed compared to Weibull distribution for March, Lubbock, TX. Scale and shape parameters were 8.1 ms^{-1} and 2.7, respectively; percent calm, max/min ratio, and hour of maximum wind speed were 1.7, 1.6, and 15, respectively.

Table 6 and figure 1 illustrate that the model reflects historical day-to-day wind variations and the wind speed variation within a day.

COMPARISON

Measured and simulated average hourly annual wind speeds for Lubbock, TX were compared. The average annual wind speed at 3-h intervals was obtained from Table 06 of Elliot et al. (1986) and adjusted to 10 m height. Annual umax, umin, and hrmax, obtained from the same source, were 6.55, 4.19 m/s, and 15 h, respectively. Umax, umin, and hrmax were used in equation 14 to simulate hourly wind speed and compared to measured wind speed in figure 2. This procedure forces agreement between simulated and observed values for daily maximum and minimum and ensures that the time of simulated maximum and observed maximum agree within frequency of reported wind speed observations. Since wind speeds often are reported only at 3-h intervals, the curves may not coincide. This was the case for the simulation in figure 2, so we set hrmax at 14 instead of the reported 15.

The form of wind speed variation is not purely sinusoidal, which causes a discrepancy between simulated time of minimum wind speed and observed time of minimum wind speed. If we were primarily interested in low wind speeds, we could easily force the agreement at low wind speeds by modifying equation 14. Also, if the pattern of daily wind speed variation deviated significantly from sinusoidal, we could replace equation 14 with one that more closely tracks wind speed variation.

Another alternative is to simply use the wind speed returned by equation 9 by each simulation. But this would produce an uncorrelated wind speed sequence. The appropriate procedure will depend on the application of the wind speed information and the consequences of an alternative procedure.

Since superimposing diurnal variation on a daily mean wind speed, drawn from a location wind speed distribution, could introduce an error in the overall distribution, we compared cumulative distributions calculated from Weibull and simulated.

Wind speeds were calculated from equation 14 for $I = 1$ to 24, 1000 times, thus simulating wind speed at 1-hour intervals for 1000 days. This simulated distribution of 24,000 wind speeds was compared to the distribution defined by equation 8. The overall agreement appears excellent (fig. 3), with a slight overestimation in the 5 to 8 m/s wind speeds and a slight underestimation in 10 to 15 m/s wind speed range by the simulation model.

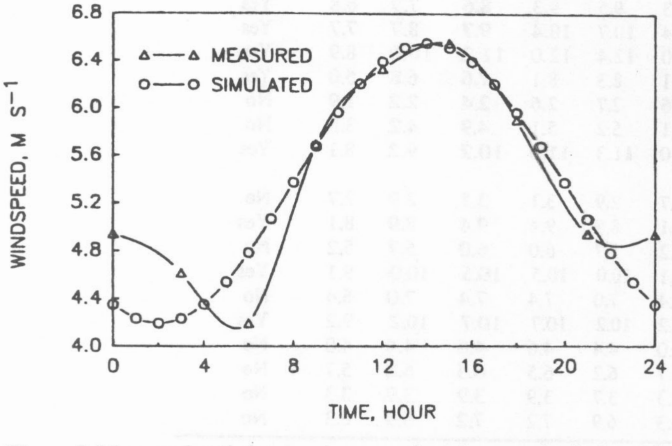

Figure 2–Measured and simulated average hourly annual wind speed compared, Lubbock, TX.

REFERENCES

Apt, K.E. 1976. Applicability of the Weibull distribution to atmospheric radioactivity data. *Atmospheric Envir.* 10: 777-782.

Corotis, R.B., A.B. Sigl and J. Klein. 1978. Probability models of wind velocity magnitude and persistence. *Sol. Energy* 20: 483-493.

Dixon, J.C. and R.H. Swift. 1984. The directional variation of wind probability and Weibull speed parameters. *Atmospheric Envir.* 18: 2041-2047.

Elliot, D.L. 1979. Adjustment and analysis of data for regional wind energy assessments. Paper presented at the Workshop on Wind Climate, Asheville, NC, 12-13 November.

Elliot, D.L., C.G. Holladay, W.R. Barchet, H.P. Foote and W.F. Sandusky. 1986. Wind energy resource atlas of the United States. DOE/CH 10093-4. Available from National Technical Information Service, Springfield, VA.

Hagen, L.J. 1990. Wind erosion prediction system: concepts to meet user needs. *J. of Soil and Water Conserv.* (Submitted)

Hagen, L.J., L. Lyles and E.L. Skidmore. 1980. Application of wind energy to Great Plains irrigation pumping. Advances in Agricultural Technology, USDA-AAT-NC-4.

Hennessey, J.P. 1977. Some aspects of wind power statistics. *J. Appl. Meteor.* 16: 119-128.

Johnson, G.L. 1978. Economic design of wind electric systems. *IEEE Transactions on Power Apparatus Systems* PAS-97(2): 554-562.

Lyles, L. 1976. Wind patterns and soil erosion in the Great Plains. In *Proceedings of the Symposium Shelterbelts on the Great Plains*, Great Plains Agr. Council Pub. No. 78: 22-30.

Lyles, L. 1983. Erosive wind energy distributions and climatic factors for the West. *J. Soil & Water Conserv.* 38: 106-109.

McWilliams, B., M.M. Newmann and D. Sprevak. 1979. The probability distribution of wind velocity and direction. *Wind Engineering* 3: 269-273.

McWilliams, B. and D. Sprevak. 1980. The estimation of parameters of the distribution of wind speed and direction. *Wind Engineering* 4: 227-238.

Nicks, A.D. and L.J. Lane. 1989. Weather generator. In USDA - Water erosion prediction project: Hillslope profile model documentation, eds. L.J. Lane and M.A. Nearing, 2.1-2.19. NSERL Report No. 2, USDA-ARS, National Soil Erosion Research Laboratory, West Lafayette, IN.

Reed, J.W. 1975. Wind power climatology of the United States. SAND 74-0348. Sandia Lab., Albuquerque, NM.

Skidmore, E.L. 1965. Assessing wind erosion forces: directions and relative magnitudes. *Soil Sci. Soc. Am. Proc.* 29: 587-590.

Skidmore, E.L. 1987. Wind-erosion direction factors as influenced by field shape and wind preponderance. *Soil Sci. Soc. Am. J.* 51: 198-202.

Skidmore, E.L. and L.J. Hagen. 1977. Reducing wind erosion with barriers. *Transactions of the ASAE* 20(5): 911-915.

Skidmore, E.L. and J. Tatarko. 1990. Wind in the Great Plains: Speed and direction distributions by month. In *Sustainable agriculture for the Great Plains*, eds. J.D. Hanson, M.J. Shaffer, and C.V. Cole, 195-213. USDA, ARS Unnumb. Pub.

Skidmore, E.L. and N.P. Woodruff. 1968. Wind erosion forces in the United States and their use in predicting soil loss. USDA-ARS, Agr. Handbook No. 346.

Takle, E.S. and J.M. Brown. 1978. Note on the use of Weibull statistics to characterize wind speed data. *J. Appl. Meteor.* 17: 556-559.

Tribbia, J.J. and R.A. Anthes. 1987. Scientific basis of modern weather prediction. *Science* 237: 493-499.

Zingg, A.W. 1949. A study of the movement of surface wind. *Agricultural Engineering* 30:11-13, 19.