United States
Department of
Agriculture

Agricultural
Research
Service

ARS-89

June 1991

Sustainable Agriculture for the Great Plains, Symposium Proceedings

Fort Collins, Colorado
January 19-20, 1989

Edited by:
Jon D. Hanson
Marvin J. Shaffer
Dan A. Ball
C. Vern Cole

Hanson, Jon D., Marvin J. Shaffer, Dan A. Ball, and C. Vern Cole. 1991. *Sustainable Agriculture for the Great Plains, Symposium Proceedings.* U.S. Department of Agriculture, Agricultural Research Service, ARS-89, 263 pp.

Sales Information

Copies of this publication may be purchased from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

ARS has no additional copies for free distribution.

Wind in the Great Plains: Speed and Direction Distributions by Month

E.L. Skidmore and John Tatarko, Agricultural Research Service and Kansas Agricultural Experiment Station, Manhattan, Kansas.

Skidmore, E.L. and J. Tatarko, 1991. Wind in the Great Plains: Speed and Direction Distributions by Month. Pages 245-263 *in:* J.D. Hanson, M.J. Shaffer, D.A. Ball, and C.V. Cole (eds.), *Sustainable Agriculture for the Great Plains, Symposium Proceedings.* USDA, ARS, ARS-89, 255 pp.

ABSTRACT

Wind erosion and drought threaten the sustainability of agriculture in the Great Plains. Strong winds constrain crop production by blowing snow off the fields, increasing potential evaporation, and eroding soil. To better cope with the wind in the Great Plains, we have developed a detailed data base. We used Wind Energy Resource Information System (WERIS) data obtained from the National Climatic Data Center for 208 locations in the Great Plains. We analyzed the WERIS data to determine scale and shape parameters of the Weibull distribution for each of the 16 cardinal directions for each month at each location. We also summarized wind direction distributions by month for each location. The wind direction summaries give the probability of wind from each of the 16-cardinal directions plus calm periods. Additionally, the monthly average ratio of daily maximum to minimum hourly wind speed, hour of maximum wind speed, and air density are given. These data indicate not only wind speed and wind direction probabilities by month but also provide additional information for calculating wind power and diurnal and hourly wind speed variations.

INTRODUCTION

The wind is of interest to many people. Wind energy developers, hydrologists, meteorologists, climatologists, farmers, ranchers, sportsmen, environmentalists, conservationists, agricultural pest managers, housewives, and others all have reasons to know about the wind.

This need to know 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. 1987) and those concerned with erosion of soil by wind (Lyles 1976, Lyles 1983, Zingg 1949, Skidmore 1965, Skidmore 1987).

Skidmore (1965) computed wind erosion force vectors from frequency of occurrence of direction by wind speed groups. The wind erosion force vectors were used to compute monthly magnitudes of wind erosion forces, prevailing wind erosion direction, and preponderance of wind erosion forces in the prevailing wind erosion direction. These factors, which indicate, respectively, potential need for wind erosion protection, proper orientation of erosion control measures, and relative merits of proper orientation of the control methods, were furnished by month for 212-locations throughout the United States (Skidmore and Woodruff 1968). The resulting handbook since has been used for conservation planning and wind erosion prediction. The prevailing wind erosion direction and preponderance data are included in the recent SCS National Agronomy Manual (1988). In that manual, magnitude of wind erosion forces was presented in an erosive wind energy distribution format, as developed by Bondy et al. (1980) and Lyles (1983).

Although these wind analyses were essential for conservation planning and wind erosion prediction with the wind erosion equation of Woodruff and Siddoway (1965), they are not adequate for the evolving wind erosion technology (Hagen 1988). The purpose of this research was to develop a wind data base suitable for use in the stochastic approaches in the current wind erosion modelling effort. The same data should benefit other scientists and resource managers needing wind data.

METHODS

We obtained the Wind Energy Resource Information System (WERIS) data base from the National Climatic Data Center on digital 9-track tape in ASCII format. This data base contains information for more than 900-locations in the U.S. and 208-locations in the Great Plains (Fig. 1). The data base was prepared by the Pacific Northwest Battelle Laboratory for the U.S. Department of Energy (Elliot et al. 1987). During 1981 and 1982, the WERIS data base was integrated into a computerized data base and transferred to the National Climatic Data Center, Ashville, North Carolina (NCC TD 9793).

Each location in the WERIS data base is identified by a unique Weather-Bureau-Army-Navy (WBAN) station number. WERIS includes data for various periods of record during 1947 through 1978 for which the anemometer height, anemometer location, and frequency of observation remained constant.

WERIS consists of 19-tables of wind statistics for each location (Table 1). Data were extracted from these tables and, in some cases, analyzed further to create a database suitable for our needs.

Figure 1. Locations in the Great Plains for which wind data are summarized.

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 modelling effort, we thought it important to archive in our data base for future studies.

We used data from WERIS Table 12 A-L, joint wind speed/direction frequency by month (Table 2), 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:

$$F(u) = 1 - \exp(-(u/c)^k) \quad (1)$$

and

$$f(u) = dF(u)/du = (k/c)(u/c)^{k-1} \cdot \exp(-(u/c)^k) \quad (2)$$

where u is wind speed, c is scale parameter (units of velocity), and k is shape parameter (dimensionless) (Weibull 1951, Apt 1976). Since anemometer heights varied from location to location, all wind speeds (Column 1, Table 2) were adjusted to a 10-m reference height according to the following:

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

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

Table 1. Summary of statistics in the Wind Energy Resource Information System (WERIS) (Elliot et al. 1987).

Table	Description	No. of Pages
01	Hourly Mean Speed and Frequency by Month	12
02	Annual Hourly Mean Speed and Frequency	1
03	Annual hourly Speed Duration	1
04	Average Wind Speed and Wind Power (Hr, Month, Season)	1
05	Maximum and Minimum Mean Hourly Wind Speed by Month	1
06	Average Wind Speed and Power (Month, Year)	1
07	Standard Deviation of Speed and Power (Month, Year)	1
08	Wind Speed Pattern Factor (Month, Year)	1
09	Number of Observations (Month, Year)	1
10	Significant Weather Parameters and Events by Month	1
11	Monthly Wind Speed Frequency	1
12	Joint Wind Speed/Direction Frequency by Month	12
13	Annual Joint Wind Speed/Direction	1
14	Annual Joint Wind Power/Direction Frequency	1
15	Wind Speed Duration by Direction by Month	12
16	Annual Wind Speed Duration by Direction	1
17	Annual Wind Power Duration by Direction	1
18	Wind Speed Persistence above Speed Threshold	1
19	Wind Direction Constancy by Direction	1
	Total No. of Pages	52

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,

$$F_1(u) = ((F(u) - F_0)/(1 - F_0)) = 1 - \exp(-(u/c)^k) \quad (4)$$

where $F_1(u)$ 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 the method of least squares applied to the cumulative distribution function, Equation (4). Equation (4) was rewritten as

$$1 - F_1(u) = \exp(-(u/c)^k). \quad (5)$$

Then by taking the logarithm twice, this becomes

$$\ln(-\ln(1 - F_1(u))) = - k \cdot \ln(c) + k \cdot \ln(u). \quad (6)$$

If we let $y = \ln(-\ln(1 - F_1(u)))$, $a = -k \cdot \ln(c)$, $b = k$, and $x = \ln(u)$, Equation (6) may be rewritten as

$$y = a + bx. \quad (7)$$

$F_1(u)$ was calculated from information in tables like Table 2 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, one can rewrite Equation (4) as

$$F_1(u) = F_0 + (1 - F_0)\{1 - \exp(-(u/c)^k)\}. \quad (8)$$

Wind direction distribution was summarized by month from the "total" row in Table 2 for each location.

Other pertinent data, obtained from the Wind Energy Resource Atlas of the United States (Elliot et al. 1987), included latitude, longitude, city, state, location name, WBAN number, period of record, anemometer height, and number of observations per 24-hour period.

We eliminated WERIS sites if they represented less than 5-years of data, the anemometer height was not known, or fewer than twelve observations were taken per day. This process of elimination reduced the number of Great Plains sites from 208 (WERIS) to 161 (Appendix A). Where more than one observation site/period remains in a metropolis area, one may pick the site with the best combination of the following:

- maximum number of hours per day observations were taken,
- longest period of record,
- one-hourly versus three-hourly observations, and
- best location of anemometer (ground mast > beacon tower > roof top > unknown location).

RESULTS

Tables 3, 4, 5, and 6 give examples of wind information we compiled for 161 Great Plains locations (Appendix A). The data are stored in computer files in ASCII format and require approximately 600 kilobytes.

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 have much utility for describing the wind speed regime. Equation (2) can be used to calculate the probability of wind for any specified 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).

An example of wind speed distributions with various scale and shape parameters is presented in both bar graph and xy plot in Figure 2. The bar graph was produced from original data as in Table 2. The wind speed data were corrected to an anemometer height of 10 m and normalized to 1.0 for total in each cardinal direction before plotting. The continuous curve (xy plot) was calculated from Equation (2); scale and shape parameters were obtained from Tables 4 and 5, respectively, corresponding to specified month and wind direction. Scale parameter of Figure 2a is located in Table 4, month 12, and direction 6; likewise, shape parameter of Figure 2a is located in Table 5, month 12, and direction 6. Weibull scale and shape parameters were used to calculate the wind speed distributions illustrated by Figure 3.

Table 2. Joint wind speed/direction frequency, March, Lubbock, Texas, (after Table 12c of WERIS).

SPEED (m sec^{-1})	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	1.7	1.7
1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.3	.1	.1	.0	.1	.1	.2	.1	.3	.1	.5	.5	.6	.4	.5	.2	.0	4.1
3	.7	.3	.5	.4	.9	.4	.6	.5	.9	.4	1.1	1.1	1.5	.8	.7	.3	.0	11.1
4	1.0	.6	.8	.4	1.1	.9	1.0	.8	1.9	.6	.8	1.2	1.6	1.2	.7	.5	.0	15.1
5	.9	.6	.8	.5	.9	.9	1.0	1.3	2.1	.9	1.2	1.2	1.6	.5	.4	.5	.0	15.4
6	.7	.7	.6	.4	.6	.5	.9	.6	1.6	1.0	1.1	1.2	.7	.6	.3	.5	.0	12.2
7	1.0	.6	.6	.4	.2	.5	.4	.5	1.6	1.0	1.4	.8	.7	.5	.3	.2	.0	10.0
8	1.0	.6	.8	.2	.5	.3	.6	.3	1.4	1.2	1.0	.6	.7	.4	.4	.2	.0	10.1
9	.8	.4	.6	.2	.3	.1	.2	.4	1.0	.8	.7	.6	.6	.4	.2	.3	.0	7.6
10	.3	.4	.2	.2	.1	.0	.1	.2	.8	.4	.2	.3	.4	.3	.1	.1	.0	4.3
11	.3	.4	.1	.1	.0	.0	.1	.1	.5	.2	.3	.3	.5	.1	.1	.1	.0	3.1
12	.2	.1	.0	.0	.0	.0	.0	.1	.0	.1	.1	.2	.4	.1	.1	.0	.0	1.6
13	.2	.1	.0	.0	.0	.0	.0	.0	.0	.8	.2	.1	.3	.2	.1	.1	.0	1.3
14	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.1	.2	.1	.1	.0	.0	.7
15	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.1	.0	.0	.0	.0	.0	.5
16	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.1	.0	.0	.0	.0	.2
17	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.0	.0	.0	.0	.1
18	.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	.1
20	.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

Table 2. Continued.

SPEED ($m\ sec^{-1}$)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	CALM	TOTAL
	WIND DIRECTION																	
26-30	.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
36-40	.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
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	6.1

Table 3. Ratio of maximum to minimum hourly wind speed, hour of maximum wind speed, air density, and occurrences of blowing dust, Lubbock, Texas.

	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
Hr. Max	15	12	15	15	18	18	18	15	15	15	12	15
Air Den.	1.14	1.13	1.11	1.09	1.07	1.06	1.05	1.06	1.07	1.09	1.12	1.13
Dust	43	56	122	119	41	28	3	3	1	4	25	49

Table 4. Weibull scale parameters (m s^{-1}) by month and direction. Wind speed was adjusted to a height of 10-meters, Lubbock, Texas.

Direction[1]	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
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

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

Table 5. **Weibull shape parameters by month and direction, Lubbock, Texas.**

Direction[1]	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
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	3.0	3.1	3.3	3.2	3.0	2.7	2.6	2.6

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

Figure 3 is intended to give a visual overview of wind speed distributions at a location. Each of the eight ridges in the figure is at 45 degree intervals and oriented in the direction of the wind it represents. For example, the two ridges that approach the axis at the left and right 0 are for wind speed distributions from the west and south, respectively. It is seen by comparing these ridges to their parallel wind speed scales that the westerly winds have a higher probability than southerly at high wind speeds but that southerly winds have a higher probability at medium wind speeds.

We determined the distribution of the coefficients of determination, r-squared, of the fit of the Weibull parameters to the wind speed data (direction and month) for four sites in each of the 10 Great Plains states; sample size equalled 7,680. The percentages of r-squared exceeding 0.98, 0.96, and 0.94 were 37, 67, and 82, respectively. In December, less than 2% of the wind was from ESE (Fig. 2a), whereas more than 27% was from the south in July (Fig. 2d). The corresponding r-squares were 0.90 and 0.99, respectively.

Wind direction distribution data, as in Table 6, are plotted for February and July in Figure. 4. No strongly favored direction is apparent for February, but the winds are strongly southern in July.

Table 6. Wind direction distribution (%) by month, Lubbock, Texas.

Direction[1]	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	10.4	10.0	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	5.74	.6	3.0	1.5	1.0	1.11	.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	3.15	.0	4.0	3.6	4.8	4.3

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

SUMMARY

These data provide detailed wind statistics useful for many purposes. Wind speed and wind direction need to be known by natural resources scientists and managers. Our immediate use is for the wind component in potential evapotranspiration models and for modelling wind erosion prediction systems.

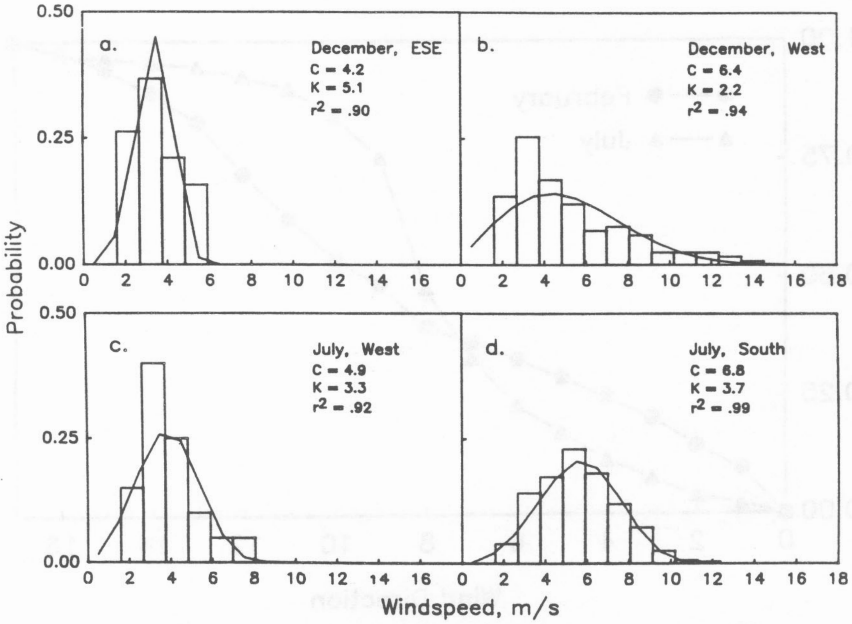

Figure 2. Wind speed distributions from summarized data (bar graph) compared to Weibull calculated distributions for various combinations of months and wind direction, Lubbock, Texas.

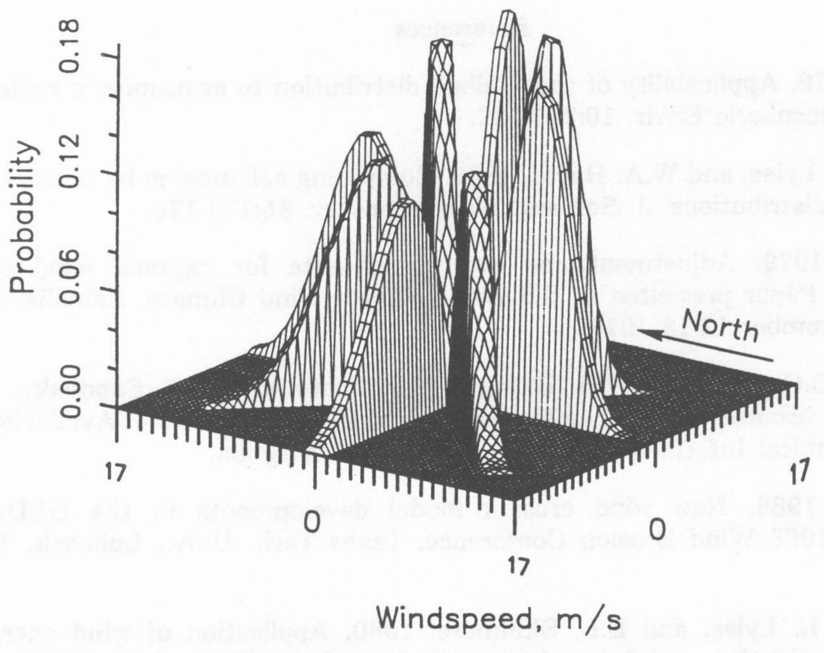

Figure 3. Wind speed probability distributions, Lubbock, Texas, March.

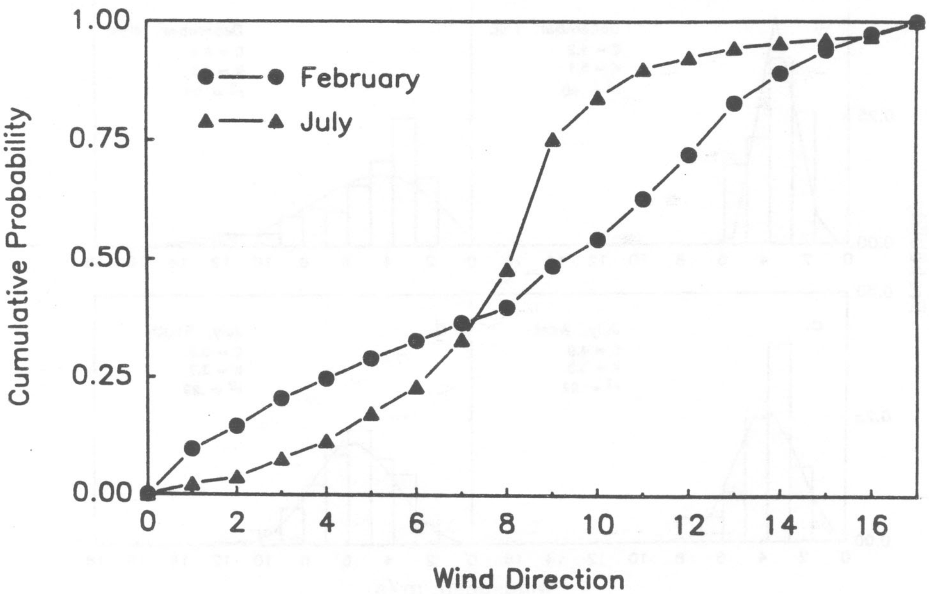

Figure 4. Wind direction probability distributions for Lubbock, Texas.

References

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

Bondy, E., L. Lyles, and W.A. Hayes. 1980. Computing soil erosion by periods using wind energy distributions. J. Soil and Water Conserv. 35:173-176.

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

Elliot, D.L., C.G. Holladay, W.R. Barchet, H.P. Foote, and W.F. Sandusky. 1987. Wind energy resource atlas of the United States. DOE/CH 10093-4. Available from National Technical Information Service, Springfield, Virginia.

Hagen, L.J. 1988. New wind erosion model developments in the USDA. *In* Proceedings 1988 Wind Erosion Conference, Texas Tech. Univ., Lubbock, Texas, pp. 104-116.

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.

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, pp. 22-30.

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

Reed, J.W. 1975. Wind power climatology of the United Stated. SAND 74-0348. Sandia Lab., Albuquerque, New Mexico, 163 pp.

SCS, U.S. Department of Agriculture. 1988. National Agronomy Manual. Second Edition. 190-V Issue I (Part 500-509). SCS, USDA, Washington, DC.

Skidmore, E.L. 1965. Assessing wind erosion forces: direction 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 N.P. Woodruff. 1968. Wind erosion forces in the United States and their use in predicting soil loss. USDA, ARS, Agr. Handbook No. 346.

Weibull, W. 1951. A statistical distribution function of wide applicability. J. Appl. Mech. 18:293-297.

Woodruff, N. P. and F. Siddoway. 1965. A wind erosion equation. Soil Sci. Soc. Am. Proc. 29:602-608.

Zingg, A.W. 1949. A study of the movement of surface wind. Agr. Engin. 30:11-13 19.

APPENDIX A

Selected wind station data for the Great Plains States (WERIS).*

Lat dd	Lat mm	Long ddd	Long mm	Elev (m)	Period[1] Start	Period[1] End	Obs	Anem. Ht (m)	Loc	WBAN Code	Type	Station Name	St
40	07	103	10	1399	480101	541231	A	8.8	R	24015	F	Akron	CO
37	27	105	52	2298	591020	781231	C	10.1	G	23061	W	Alamosa	CO
38	49	104	43	1857	670401	781231	A	6.7	G	93037	W	Colorado Springs	CO
39	42	104	45	1697	500801	590331	C	19.8	R	93032	N	Denver	CO
39	46	104	53	1622	531016	600707	A	21.9	R	23062	W	Denver/Stap. Inter. Air.	CO
39	39	106	55	1982	480101	641231	A	18.6	R	23063	F	Eagle	CO
39	07	108	32	1474	500228	640919	A	17.7	B	23066	W	Grand Junction	CO
38	03	103	31	1278	550607	640409	A	9.8	R	23067	F	La Junta	CO
38	14	104	38	1465	480101	540630	A	11.0	R	23068	W	Pueblo	CO
38	17	104	31	1421	620319	781231	A	6.7	G	93058	W	Pueblo	CO
37	15	104	20	1753	570201	640930	A	13.1	R	23070	F	Trinidad	CO
37	40	95	29	299	591201	641231	A	16.2	R	13981	F	Chanute	KS
39	33	97	39	449	620601	781231	A	6.4	G	13984	W	Concordia	KS
37	46	99	58	796	610421	781231	A	6.1	G	13985	W	Dodge City	KS
39	03	96	46	324	610401	701231	A	4.0	G	13947	A	Ft. Riley	KS
39	22	101	42	1112	500609	640322	A	9.4	R	23065	W	Goodland	KS
37	55	97	54	479	521001	580431	A	18.3	R	93905	N	Hutchinson	KS
38	50	94	53	328	590915	700131	A	4.3	G	93909	N	Olathe	KS
38	52	98	49	568	530824	641231	A	8.8	R	93997	F	Russell	KS
38	48	97	38	392	560401	650531	A	4.3	G	13922	A	Salina	KS
39	04	95	38	269	640810	781231	A	6.1	G	13996	W	Topeka	KS
38	57	95	40	324	580401	701231	A	4.0	G	13920	A	Topeka/Forbes	KS
37	39	97	25	404	540101	641231	A	9.4	G	03928	W	Wichita	KS
37	38	97	16	432	480101	531130	A	21.3	R	13998	W	Wichita	KS
37	37	97	16	414	600905	701231	A	21.3	R	03923	A	Wichita/McCon	KS
45	48	108	32	1092	650101	781231	A	7.6	G	24033	W	Billings	MT

45	57	112	30	1689	480101	601231	A	18.0	R	24135	F	Butte	MT
48	36	112	22	1174	591004	781231	A	6.1	G	24137	F	Cut Bank	MT
45	15	112	33	1592	510619	631029	A	9.1	R	24138	F	Dillon	MT
48	13	106	37	696	680601	781231	A	6.1	G	94008	W	Glasgow	MT
48	24	106	31	853	610608	680630	A	4.0	G	94010	A	Glasgow	MT
47	31	111	10	1056	580401	681130	A	4.6	G	24112	A	Great Falls	MT
47	29	111	21	1124	480101	590202	A	22.9	R	24143	W	Great Falls	MT
48	33	109	46	788	670101	781231	A	6.1	G	94012	W	Havre	MT
46	36	112	00	1188	610920	781231	A	6.1	G	24144	W	Helena	MT
48	18	114	16	908	640701	781231	A	6.1	G	24146	W	Kalispell	MT
47	03	109	27	1236	491221	620815	A	10.4	R	24036	F	Lewiston	MT
45	40	110	32	1399	480101	530704	A	17.4	B	24150	F	Livingston	MT
46	26	105	52	802	480101	641231	A	12.2	G	24037	F	Miles City	MT
46	55	114	05	980	650101	781231	A	6.1	G	24153	W	Missoula	MT
47	11	114	52	823	480101	531130	A	17.7	B	24159	W	Superior	MT
45	52	112	06	1311	480101	541231	A	9.1	G	24161	F	Whitehall	MT
42	51	103	00	1046	480101	541231	A	17.7	B	24017	F	Chadron	NE
40	58	98	19	567	611202	781231	A	6.1	G	14935	W	Grand Island	NE
40	51	96	46	364	720901	781231	A	6.1	G	14939	W	Lincoln	NE
41	59	97	26	472	480101	590909	C	11.0	R	14941	W	Norfolk	NE
41	08	100	41	848	640812	781231	A	6.1	G	24012	W	North Platte	NE
41	18	95	54	304	630401	781231	A	6.1	G	14942	W	Omaha	NE
41	07	95	54	312	600501	701231	A	3.7	G	14949	A	Omaha/Offutt	NE
41	52	103	36	1204	640802	781231	A	6.1	G	24028	W	Scottsbluff	NE
41	08	103	02	1231	491221	541231	A	7.9	R	24030	F	Sidney	NE
46	46	100	45	507	611017	781231	A	6.1	G	24011	W	Bismarck	ND
46	47	102	48	792	481201	640728	A	9.1	R	24012	F	Dickinson	ND
46	54	96	48	278	610626	781231	A	6.1	G	14914	W	Fargo	ND
47	56	97	05	259	491105	581231	A	14.3	R	14916	W	Grand Forks	ND
46	55	98	41	456	481201	541231	A	8.8	R	14919	W	Jamestown	ND
48	16	101	17	526	620629	781231	A	6.1	G	24013	F	Minot	ND
48	25	101	20	504	600501	650228	A	5.5	G	94011	A	Minot	ND
48	11	103	38	581	670823	781231	A	3.1	G	94014	W	Williston	ND
48	09	103	37	578	500301	611231	C	15.2	R	24014	W	Williston/Wbo	ND

Lat dd	Lat mm	Long ddd	Long mm	Elev (m)	Period[1] Start	Period[1] End	Obs	Anem. Ht (m)	Loc	WBAN	Code Type	Station Name	St
32	51	106	05	1241	590501	701231	A	4.0	G	23002	A	Alamogordo	NM
35	03	106	37	1620	650316	781231	A	11.9	R	23050	W	Albuquerque	NM
32	20	104	16	990	480701	541231	A	15.2	R	93033	F	Carlsbad	NM
34	23	103	19	1305	600701	691031	A	4.0	G	23008	A	Clovis	NM
31	49	107	28	1229	480701	541231	A	8.5	G	23058	F	Columbus	NM
36	45	108	14	1677	530323	641231	A	10.4	R	23090	F	Farmington	NM
35	31	108	47	1971	730101	781231	A	6.1	G	23081	W	Gallup	NM
32	41	103	12	1123	480701	541231	A	10.7	R	93034	F	Hobbs	NM
32	22	106	29	1292	570901	621231	A	4.6	G	23039	A	Las Cruces	NM
35	39	105	09	2092	480701	641231	A	7.9	R	23054	F	Las Vegas	NM
35	05	106	01	1900	480701	541231	A	8.2	G	23056	F	Otto	NM
36	45	104	30	1945	480701	530831	A	8.5	R	23052	W	Raton/Crews	NM
33	24	104	32	1106	510501	600730	A	15.8	R	23043	W	Roswell	NM
33	18	104	32	1110	570401	630331	A	4.6	G	23009	A	Roswell/Walk.	NM
35	37	106	05	1934	480701	541231	A	8.5	R	23049	F	Santa Fe	NM
33	14	107	16	1471	500601	641231	A	7.3	R	93045	W	Truth Or Con.	NM
35	11	103	36	1237	590918	781231	A	6.7	G	23048	F	Tucumcari	NM
35	06	108	48	1965	581014	721231	A	9.8	R	93044	W	Zuni	NM
34	39	99	16	414	560803	701231	A	3.7	G	13902	A	Altus	OK
34	18	97	06	264	480701	541231	A	9.1	R	13965	F	Ardmore	OK
35	22	99	12	588	580801	690331	A	4.0	G	03932	A	Clinton	OK
36	20	97	54	393	490101	590131	A	11.6	t	13909	A	Enid	OK
34	39	98	24	369	600720	701231	A	4.0	G	13945	A	Ft. Sill	OK
36	18	99	46	669	480701	641231	A	7.6	R	13975	F	Gage	OK
35	00	99	03	474	490201	541231	A	8.2	R	93986	W	Hobart	OK
35	25	97	23	384	590401	701231	A	4.0	G	13919	A	Oklahoma City	OK
35	24	97	36	391	651028	781231	A	6.1	G	13967	W	Oklahoma City	OK
36	44	97	06	309	480701	541231	A	20.4	G	13969	F	Ponca City	OK
36	12	95	54	204	601228	781231	A	7.0	G	13968	W	Tulsa	OK
45	27	98	26	396	640701	781231	A	6.1	G	14929	W	Aberdeen	SD
44	23	98	13	392	620110	781231	A	6.1	G	14936	W	Huron	SD
44	03	101	36	673	480101	541231	A	8.2	R	24024	F	Philip	SD
44	23	100	17	525	620607	781231	A	6.1	G	24025	F	Pierre	SD
44	03	103	04	966	501101	641231	A	9.8	R	24090	W	Rapid City	SD

44	09	103	06	980	550721	701231	A	4.0	G	24006	A	Rapid City	SD
43	34	96	44	437	611125	781231	A	5.2	G	14944	W	Sioux Falls	SD
44	55	97	09	527	480909	541231	A	7.6	R	14946	W	Watertown	SD
32	26	99	41	537	600505	781231	A	6.1	G	13962	W	Abilene	TX
32	26	99	51	542	620501	701231	A	4.0	G	13910	A	Abilene/Dyess	TX
27	44	98	02	55	480701	541231	A	8.2	R	12932	F	Alice	TX
35	14	101	42	1099	610503	781231	A	7.0	G	23047	W	Amarillo	TX
30	18	97	42	183	610701	781231	A	6.1	G	13958	W	Austin	TX
30	12	97	40	155	620906	701231	A	5.2	G	13904	A	Austin/Bergs	TX
28	22	97	40	62	620201	720228	A	4.3	G	12925	N	Beeville	TX
32	14	101	30	784	590507	701231	A	4.6	G	23005	A	Big Spring	TX
25	54	97	26	10	480701	610120	A	17.1	R	12919	W	Brownsville	TX
30	40	96	33	84	511001	580630	A	7.3	R	13905	A	Bryan	TX
27	46	97	30	17	600916	781231	A	7.0	G	12924	W	Corpus Christi	TX
27	41	97	17	6	610713	720228	A	3.7	G	12926	N	Corpus Christi	TX
27	41	97	27	14	490201	580331	A	26.2	R	12946	N	Corpus Christi	TX
28	27	99	13	141	491001	541231	A	8.2	R	12947	F	Cotulla	TX
36	01	102	53	1217	481201	540914	A	19.2	R	93042	F	Dalhart	TX
32	44	96	58	143	660814	781231	A	4.6	G	93901	N	Dallas	TX
32	51	96	51	159	580429	740131	A	6.1	G	13960	W	Dallas/Love	TX
29	22	100	55	314	640301	781231	A	7.0	G	22010	W	Del Rio	TX
29	22	100	47	327	530630	590326	A	12.2	R	22001	A	Del Rio/Laug	TX
31	48	106	24	1200	480701	610430	A	25.9	R	23044	W	El Paso	TX
31	50	106	24	1196	560101	660430	A	4.0	G	23019	A	El Paso/Biggs	TX
31	04	97	49	312	650101	700630	C	3.0	G	03902	A	Ft. Hood	TX
31	08	97	43	280	650501	700630	A	5.5	G	03933	A	Ft. Hood	TX
32	50	97	03	175	530501	630522	A	25.9	R	03927	W	Ft. Worth	TX
32	46	97	27	188	570501	701231	A	4.0	G	13911	A	Ft. Worth	TX
29	16	94	51	8	480701	581217	A	14.0	R	12923	W	Galveston	TX
29	59	95	21	37	690601	781231	A	6.1	G	12960	W	Houston	TX
29	39	95	17	16	500621	600728	A	26.5	R	12918	F	Houston/Hobby	TX
30	30	99	46	521	500401	641231	A	7.3	R	13973	F	Junction	TX
27	30	97	48	18	670201	781231	A	6.1	G	12928	N	Kingsville	TX
27	32	99	28	154	650401	701231	A	6.1	G	12907	A	Laredo	TX

Lat dd	Lat mm	Long ddd	Long mm	Elev (m)	Period[1] Start	Period[1] End	Obs	Anem. Ht (m)	Loc	WBAN Code	Type	Station Name	St
27	32	99	28	154	470623	610228	A	11.9	R	12920	W	Laredo	TX
33	39	101	50	990	500628	641231	A	20.7	R	23042	W	Lubbock	TX
33	36	102	03	1015	641103	701231	C	3.0	G	23021	A	Lubbock/Reese	TX
31	14	94	45	89	480901	560330	A	7.9	R	93987	F	Lufkin	TX
30	15	103	53	1481	480701	541231	A	17.1	R	93035	F	Marfa	TX
31	56	102	12	871	591204	781231	A	6.7	G	23023	W	Midland	TX
32	47	98	04	286	480601	641231	A	8.5	R	93985	F	Mineral Wells	TX
28	43	96	15	5	490401	581231	A	8.5	R	12935	F	Palacios	TX
29	57	94	01	9	601118	781231	A	6.1	G	12917	W	Port Arthur	TX
26	10	97	20	9	600725	610531	d	4.0	G	12957	N	Port Isabell	TX
31	22	100	30	585	610915	781231	A	6.1	G	23034	W	San Angelo	TX
29	23	98	34	208	590116	701231	A	4.0	G	12909	A	San Antonio	TX
29	32	98	17	230	600501	701231	A	4.0	G	12911	A	San Antonio	TX
29	32	98	28	243	610901	781231	A	7.0	G	12921	W	San Antonio	TX
29	21	98	27	182	530701	600331	A	21.6	R	12931	A	San Antonio	TX
29	53	97	52	178	510501	560831	A	7.9	R	12910	A	San Marcos	TX
33	43	96	40	233	570401	701231	A	4.3	G	13923	A	Sherman	TX
32	22	95	24	173	500504	541231	A	21.6	R	13972	W	Tyler	TX
28	51	96	55	33	640701	781231	A	6.1	G	12912	W	Victoria	TX
28	47	97	05	35	530828	610530	C	11.6	R	12922	W	Victoria/Aloe	TX
31	37	97	13	157	640218	781231	A	7.0	G	13959	W	Waco	TX
31	38	97	04	145	580501	660731	A	4.0	G	13928	A	Waco/Connally	TX
33	58	98	29	307	610424	781231	A	6.4	G	13966	W	Wichita Falls	TX
31	47	103	12	858	480701	541231	A	9.1	R	23040	W	Wink	TX
42	55	106	28	1622	640812	781231	A	6.1	G	24089	W	Casper	WY
41	09	104	49	1871	650101	781231	A	10.1	G	24018	W	Cheyenne	WY
42	45	105	22	1486	480101	541231	A	17.7	B	24019	W	Douglas	WY
41	24	110	25	2136	480101	541231	A	18.3	u	24118	W	Ft. Bridger	WY
42	49	108	44	1697	620401	730919	A	9.8	R	24021	W	Lander	WY
41	19	105	41	2217	480101	541231	A	19.5	u	24022	W	Laramie	WY
41	48	107	12	2067	550101	641231	A	8.5	R	24057	W	Rawlins	WY
41	36	109	04	2056	600727	781231	A	6.1	G	24027	F	Rock Springs	WY
44	46	106	58	1203	640903	781231	A	6.1	G	24029	W	Sheridan	WY

[1] Format for PERIOD is yymmdd--year/month/day.

* Stations are grouped alphabetically by state name. The WBAN station code is a unique identification code number for each station. Other codes are as follows:

LAT = Latitude: dd = degrees, mm = minutes

LONG = Longitude: ddd = degrees, mm = minutes

ELEV = Elevation above mean sea level in meters

PERIOD = Period of record
- yy = year
- mm = month
- dd = day

NOTE: The change in observation frequency from hourly to 3-hourly occured near the end of 1964, 1970, and 1972 for civilian agencies, Air Force, and Navy, respectively.

OBS = Number of hours/day observations were taken
- A = 24
- B = 19-23
- C = 12-18

LOC = Type of structure on which the anemometer was located
- R = Roof-Top
- G = Ground Mast
- B = Beacon Tower
- U = Unknown Location
- E = Estimated Wind, No Anemometer

TYP = Type of agency responsible for operation
- A = Air Force
- N = Navy
- W = Weather Service
- F = FAA

ANEM. HT = Anemometer height above ground in meters