CLIMATE OF MINNESOTA

Part XIV—Wind Climatology and Wind Power

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Contents

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CLIMATE OF MINNESOTA—Part XIV

Wind Climatology and Wind Power

I. Introduction

Wind is simply air in motion in response to the differential heating of the earth's surface. Because it transports heat, moisture, and other atmospheric properties from one point to another, the wind is an essential part of the atmospheric heat engine.

The primary objective of this bulletin is to present a climatology of wind within the state of Minnesota. A secondary objective is to provide a guide to the possibilities of wind as a practical energy source.

Recently there has been renewed interest in developing energy sources other than nonrenewable fossil fuels. Wind is again being considered as an energy source and it is a matter of great practicality to try to harness it in case of actual or threatened energy shortages. Detailed information on the energy content of winds should be available.

II. General Characteristics of Wind

Like solar energy received at the earth's surface, wind is not a constant energy source. This intermittentcy poses immediate problems if wind is to be used as an energy source. There are two basic reasons for this variation in atmospheric motion. The first one is predictable: winds fluctuate with the atmosphere's diurnal and seasonal heating and cooling caused by the daytime presence and nighttime absence of the sun, as well as the position of the earth in its annual orbit about the sun. In addition, this regular cycle of heating and cooling is altered by irregular variations in cloud cover and wind flow caused by mobile weather pressure systems.

Local topographic features, whether natural or manmade, also influence air movement. Any object that modifies the flow of wind across the surface of the earth decreases the predictability of both wind speed and direction. Even smooth-surfaced features, which reduce the wind speed to some degree, can further modify air motion if adjoining surfaces have different heating characteristics. One example of this is the familiar land-sea (lake) breeze effect found along the margins of large bodies of water. The modification in air movement there is due to a temperature difference between land and water.

Although previous points emphasize the unpredictability of wind, there are three generalizations or rules regarding its predictability that should be noted. These generalizations are climatologically true. That is, although they may not hold every day or every year, they will prove true over a period of time.

a. Wind speed is usually greater during the day than at night.
b. Wind speed usually increases with height above the surface of the earth.
c. In Minnesota wind speed is usually greatest in April and November and least in July and August.

The first generalization states that winds are generally greater in the day than at night. Since wind is the direct result of differential solar heating, wind adjacent to the earth's surface shows a marked diurnal effect—it generally increases during the day and decreases at night (Figure 1).

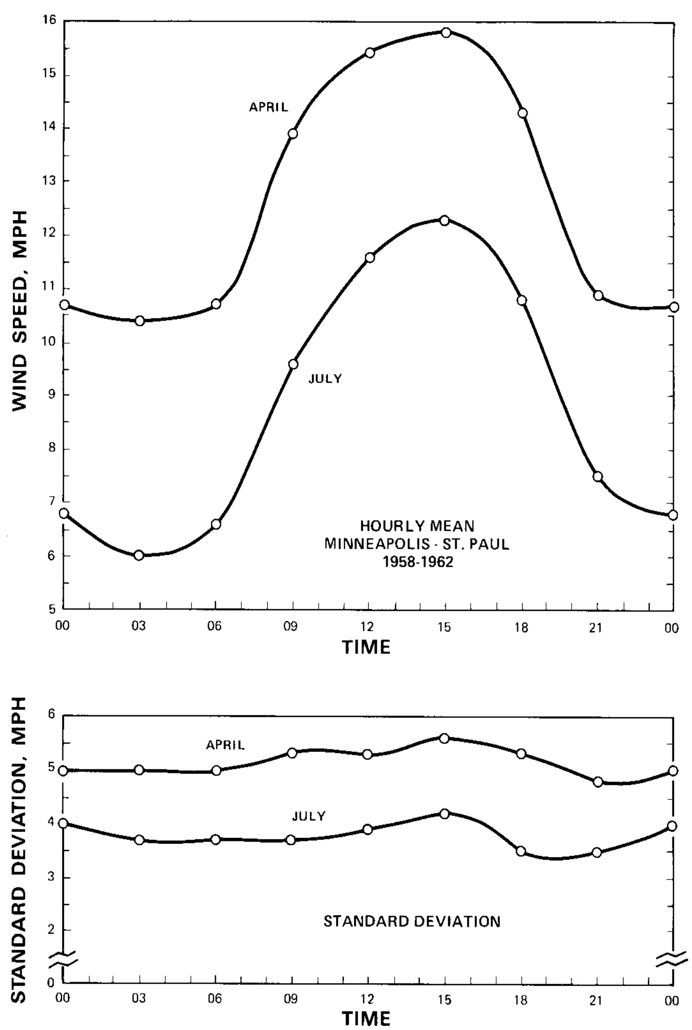


Figure 1. Mean hourly march of wind speed (upper) and standard deviation of hourly wind speeds (lower) in April and July at Minneapolis-St. Paul, 1958-1972.

Several factors can mitigate this diurnal effect. Soil supporting actively transpiring vegetation, which consumes energy in evapotranspiration and photosynthesis, has less energy available to heat the air and thus reduces the diurnal wind variation. A soil bare of vegetation, by comparison, has little effect on wind variation. An additional decrease in variation may arise from the physical obstruction created by the vegetation. Similarly, snow cover reduces the diurnal variation in wind speed because it increases reflection and decreases absorption of solar radiation, and therefore decreases energy available to heat the air. This is not to be confused with the seasonal wind variation, in which higher winds occur in winter due to greater winter north to south continental-scale temperature gradients. Occasionally, mobile pressure systems moving across the state can mask the diurnal effect of winds.

In the temperate regions, particularly over land, the daytime maximum and nighttime minimum wind speeds hold true for a relatively shallow portion of the atmosphere. A reversal takes place in a so-called "intermediate layer" (6), at from about 150 to 300 feet above the surface, so that the maximum occurs at night and the minimum during the day. The height of this intermediate layer is a direct function of surface friction and daytime surface heating. Without measurement it is difficult to estimate the height of the "intermediate layer." Over the gently rolling terrain typical of the Ames, Iowa, area, an eight-year hourly average of winds at 105 feet still showed a marked daytime maximum in each month of the year (17). Evidently that level was still well below the "intermediate layer" of the wind speed reversal. The "intermediate layer" decreases in height in winter, in high pressure areas, and with cloudy conditions. It occurs because there is more energy carried downward in higher speed eddies than is carried upward in the ascending eddies of slower speeds originating at the surface.

The second generalization is that air speed usually increases with altitude. At lower altitudes the friction of the earth's surface retards air motion. The effect of friction on both wind speed and wind direction may be observed from a few tens of feet to a few thousand feet, depending upon the smoothness of the surface. The effect of altitude on wind speed has been known for years; windmills traditionally have been built as far above the surface as practical to take advantage of the higher and more constant wind motion.

The third generalization states that wind speed in Minnesota is greatest in April and November and least in July and August. Minnesota's wind pattern has its origin in large scale heat transference. The inequality of heat reception between the equator and poles and the attempt to equalize the resulting temperature differences produces the nearly constant state of motion of the earth's atmosphere. In the middle latitudes this motion usually takes the form of organized and mobile weather pressure systems with a "polar front" marking the transition zone between polar and tropical air. The mobile weather pressure systems associated with the polar front most frequently migrate across the state moving northward in April and southward in November, thus causing the greatest frequency of higher winds.

The generally higher winter wind speed is the result of the greater temperature difference existing in both hemispheres during their respective winter seasons. While temperatures in the tropics are nearly constant throughout the year, in the temperate and polar regions there is a marked decrease in the winter, thus creating the greater wintertime temperature differential between equator and pole.

While the unpredictability of the wind, particularly in the short term, has been noted, the three rules provide a basis upon which a measure of predictability can be obtained. These generalizations, coupled with a climatological or longterm analysis of the wind, allow rather accurate predictions to be made. For, while the weather can show large and rapid variations from one moment to another, the climate is far more stable. Thus, to ensure optimum success, a wind energy system should be designed to take advantage of the climatology of a region.

III. Wind Measurement

A. General

Wind is ordinarily described by direction and speed. Wind direction, always recorded as the direction *from* which it is blowing, is detected with a wind vane. Wind speed is recorded with an anemometer. Usually only the horizontal component is measured; the vertical component, normally the smaller of the two, is seldom measured. Data analyzed in this bulletin include only measurements of the horizontal wind component.

Leonardo da Vinci is credited with describing the first wind sensor, a pressure plate type of anemometer (8), but such a device was apparently first constructed by Robert Hooke in 1667.

Wind speed has been and is measured in a number of different ways. In some cases differences consist only of different length and time units as in miles (feet) per hour (second), as in Table 1. A most interesting method, common 40 years ago and occasionally still referred to, was devised in 1805 by Sir Francis Beaufort, a British Navy hydrographer, for whom the Beaufort Sea off the north coast of Alaska was named (7). In this Beaufort wind scale, adopted for use in international weather communications in 1870 (8), wind speeds were classified in terms of the state of the sea and the sails of the ship. It let sailors without an anemometer estimate wind speeds with surprising accuracy. Later the Beaufort wind scale was adapted to land use based upon the movement of natural objects in the wind such as leaves, tree branches, and so on (21).

The wind speed data in this bulletin were obtained with the 3-cup anemometer with the cups rotating about a vertical axis. Until January 1, 1928 (8), a 4-cup anemometer was used by the U.S. Weather Bureau (renamed National Weather Service in 1972).

Table 1. Wind speed conversion factors (10).

1 mile per hour	=	1.467 feet per second
	=	0.868 knot
	=	1.609 kilometers per hour
	=	0.447 meter per second
1 knot	=	1.000 nautical mile per hour
	=	1.152 miles per hour
	=	1.853 kilometers per hour
	=	0.515 meter per second
1 kilometer per hour	=	0.278 meter per second
	=	0.539 knot
	=	0.621 mile per hour
1 meter per second	=	3.600 kilometers per hour
	=	1.942 knots
	=	2.237 miles per hour

The metal 3-cup anemometer is not an ideal instrument due to its relatively large mass and to gear friction. Measurement errors can result. A wind of about 2-4 mi/hr is required to move an anemometer at rest. Conversely it tends to "over-run" or keep rotating for a time after a gust has passed, since it slows down more slowly than it speeds up (5, 19).

B. Transfer of Wind Measurement to Other Locations and Heights

Wind is measured at only a few locations in the state and data analyzed in this bulletin come from eight stations. Because of the limited number of stations results at one site have to be used to answer questions concerning another location. The data have to be translated from one site to another by interpolation between stations with available data, a method obviously subject to error.

Several factors make this transference of data to another site difficult. One is the nature of the surface of the surrounding countryside. In Minnesota this can vary from a smooth, featureless plain, as in the Red River Valley, to a rolling and relatively rough topography typical of extreme southeastern Minnesota. A further modification of the surface occurs if the site is agricultural or urban. Another factor is station altitude relative to the surrounding area, a point of particular importance at the Duluth and Rochester stations. A third factor is anemometer height, since wind speed almost always increases with altitude. Figure 2 illustrates the effects that surface roughness and anemometer height can have on the measured wind speed.

The transfer of meteorological data is often thought of in the horizontal or spatial sense as discussed earlier. It may also be necessary to translate the data from one height to another. That is not necessarily as great a problem; empirical formulas permit the calculation of the wind speed at a height different from that of the measurement. Although these formulas may not hold true for instantaneous values, they are fairly reliable in a climatological or long-term sense. This is in marked contrast to the horizontal transfer of wind data some miles distant from the place of measurement. In that

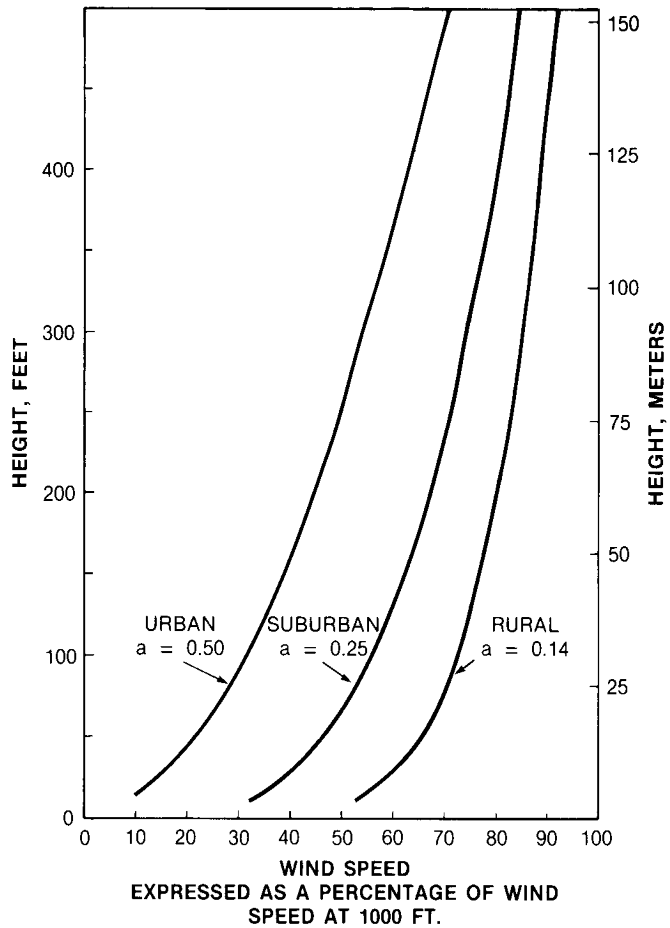


Figure 2. Typical variation of wind speed with altitude for urban, suburban, and rural surfaces. After Duncan (4), and Toops and Waite (21).

case, only qualitative estimates can usually be made as to the applicability of the data, unless the transfer is across uniform terrain.

Possible errors arise from local differences in the physical environment such as obstruction to wind movement and height of the measurement—not only station altitude but more particularly the height of the wind measurement system above the immediate surface. Whether a meteorological measurement accurately represents area conditions is a common question that becomes more acute the closer the measurement is made to the earth. This problem is of special importance in wind measurement, since both surface obstructions and typography can reduce wind speed and to a lesser degree alter wind direction.

A power law wind formula is frequently used to calculate the wind speed at a height other than that at which the wind is measured. The formula is $U_2/U_1 = (Z_2/Z_1)^a$, where U is wind speed, Z is height, and "a" is a constant. This formula is widely used by engineers (12). The subscripts in $U_2/U_1 = (Z_2/Z_1)^a$ refer to measurement heights, with subscript 1 always the lower height. To determine the wind speed at height Z_1, which is lower than height Z_2 at which the wind is measured, U_1 is the unknown. If the speed at a height greater than the measured height is required, U_2 becomes the unknown speed at height Z_2, while U_1 is the measured speed at height Z_1.

Actually "a" is not a true constant but varies with the temperature structure of the lower atmosphere, roughness of the surface over which the wind is blowing, and the height above the surface. Due to its dependence upon the temperature profile of the lower atmosphere, the value of "a" also varies with the time of day and season of the year. Typical values of "a" for urban, suburban, and rural sites are shown in Figure 2.

Takle, et al. (17) investigated the diurnal and monthly variation of "a" values using Ames, Iowa, tower data with winds measured at 4, 8, 16, and 32 meters. In agreement with Munn (12), they found a seasonal and, more particularly, a marked diurnal difference in the value of "a." Their data show that the value of "a" remained near 0.12 during daylight hours, but during nighttime averaged about 0.25 for the year. This is the result of a "de-coupling" which takes place between the air adjacent to the earth's surface within a temperature inversion (a common nighttime feature close to the earth's surface) and the air above. That is, the air within the inversion layer is more or less physically separated from the air above the inversion. As a result, large wind speed changes with height can occur in passing through the inversion. Takle and Brown (18) determined that the power law in which $a = 1/7$ or 0.14, fit their Iowa wind data quite well for moderate to high wind speed conditions. Reed et al. (14) found the 1/7 power law appropriate for New Mexico applications, particularly in the 10 to 30 mi/hr range that is the major source of power to most energy systems. They concluded that, pending detailed analyses for particular sites, the "a" value of 0.14 (1/7) is adequate for planning purposes in New Mexico. Peterson and Hennessy (13) similarly concluded that the power law exponent of 1/7 is "adequate for realistic but conservative estimates of the available wind power."

Although short period or instantaneous wind measurements have frequently been used to extrapolate measurements at greater heights, the results obtained should be viewed with caution regardless of the wind speed-height equation used. The wind seldom moves over the earth's surface in an orderly and predictable manner; the motion at any instant is usually turbulent and resistant to prediction. In addition, the "intermediate layer" in which the nighttime wind speed maximum is found begins at about 150 feet. It is only with time-averaged data that a semblance of order can be established and a mathematical description attempted. Because of the variety of conditions that can exist near the earth's surface, no wind formula has yet been devised which adequately describes the wind profile under all conditions. For this reason the relatively simple power law formula was used on time-averaged wind data along with the commonly accepted value of "a". Therefore, the results shown in this bulletin, while perhaps lacking in great accuracy, can at least be compared with other studies and locations.

IV. Wind Data

A. Description

The data used in this study are part of the hourly wind speed observations taken at National Weather Service and Federal Aviation Agency stations. The weather observers use an instantaneous wind speed indicator to estimate an average wind speed for a one-minute period each hour. Although questions have been raised as to whether such a sample is representative, it is probably acceptable for most purposes when taken over a period of years.

B. Source

The station records analyzed are those of Duluth, Fargo, Minneapolis-St. Paul, Sioux Falls, Hibbing, International Falls, Redwood Falls, and Rochester. Wind data of the first four stations were obtained from National Weather Service publications (23, 24, 25, 26). Summarized but unanalyzed data from the Hibbing, International Falls, Redwood Falls, and Rochester stations were obtained from B.F. Watson, consulting meteorologist, Roseville, Minnesota. Hibbing and Redwood Falls are Federal Aviation Agency stations. The others are National Weather Service stations. Details of each measurement site are given in Table 2.

The Minnesota wind data, like most wind data, lack measurement uniformity. The height and location of the wind measuring equipment of the eight stations varies greatly. For example, at Minneapolis-St. Paul the wind was measured at 75 feet above ground from 1951-1958, and at 21 feet thereafter. Although data were corrected to a standard height of 20 feet this disparity should be noted, since it may have some effect upon the application of the data.

The wind data for Duluth, Fargo, and Sioux Falls were also corrected to a uniform height of 20 feet. This height is in accordance with the National Weather Service, which standardized anemometers to a 20 foot height above grassy areas well removed from buildings or other obstructions. In addition, several recent studies have normalized wind measurements to the standard 20 foot height. In this study corrections were made using the generally accepted power law formula $(U_2/U_1) = (Z_2/Z_1)^a$. The value assigned to "a" was 0.14 which is typical of many rural and airport sites. The wind data at Hibbing, International Falls, Redwood Falls, and Rochester, obtained with anemometers at or close to 20 feet were not altered. No attempt was made to alter the wind directions at any of the stations. Interestingly, a standard height of 21 feet above a grassy area removed from buildings or other obstructions was adopted some time after 1960. This seemingly odd

Table 2. Location and description of stations.[1]

Station & period	Location	Latitude & longitude	Station altitude	Anemometer height	Remarks
Duluth 1951-1960	Williamson-Johnson Municipal Airport	46° 50′N 92° 11′W	1408 ft	53 ft	Anemometer mounted on a mast 15-20 ft above a curved roof; Vegetation mainly wooded within 10 mi radius from N-NE and SW-N; to E-S residential with wooded areas; Terrain gently rolling within 10 mi except Lake Superior is 8 mi E and 5 mi SE at 602 ft; station is 800 ft higher than Lake Superior and 50-100 ft higher than North Shore Ridge bluffs which rise to 700 ft above the lake within a distance of 1-1½ mi of station; height and abruptness of bluffs tends to increase (funnel effect) wind speeds from a NE-E direction; bluffs plus lake effect produce a higher than normal frequency of easterly winds.
Fargo, ND 1951-1960	Hector Airport	46° 54′N 96° 48′W	895 ft to Jan 1960, and 896 ft thereafter	47 ft to Nov 1953 and 86 ft thereafter	Anemometer mounted on a mast above a building; Vegetation agricultural or open without buildings within 10 mi radius; Topography flat within 1 mi radius and gently rolling to flat within 10 mi radius.
Hibbing 1964-1973	Chisholm-Hibbing Airport	42° 23′N 92° 51′W	1347 ft	28 ft	Anemometer in an unobstructed runway exposure; Vegetation agricultural or wooded within 10 mi radius; Terrain flat within 1 mi radius becoming hilly (ore dumps) within 10 mi radius; many lakes to N-NE, fewer lakes to NW.
International Falls 1964-1973	Municipal Airport	48° 34′N 93° 23′W	1179 ft	34 ft to Aug 1965 and 20 ft thereafter	Anemometer mounted on building with flat roof up to August, 1965, afterwards at 20 ft with a runway exposure; Vegetation wooded within 10 mi radius; Terrain generally level within 10 mi radius.
Minneapolis-St. Paul 1951-1960	International Airport (Wold Chamberlain Field)	44° 53′N 93° 13′W	830 ft to Jan 1960, 822 ft thereafter	75 ft to Sept 1958; 21 ft thereafter	Anemometer mounted on mast on building to September, 1958, afterwards at 21 ft with a runway exposure; Vegetation largely wooded within 10 mi radius except for urban centers about 5½ mi NNW and 5½ NE; Terrain flat within 1 mi radius and gently rolling with 10 mi radius; Mississippi River gorge ½ mi SE and 200 ft lower than airport.
Redwood Falls 1964-1973	Municipal Airport	44° 33′N 95° 05′W	1025 ft	21 ft	Anemometer at 21 ft with a runway exposure; Vegetation agricultural with some wooded areas within 10 mi radius; Terrain gently rolling within 10 mi radius; Minnesota river valley ½ mile north and 200-250 ft lower than general terrain.

Table 2. Location and description of stations.[1] (continued)

Station & period	Location	Latitude & longitude	Station altitude	Anemometer height	Remarks
Rochester 1964-1973	Municipal Airport	43° 55′N 92° 30′W	1297 ft	20 ft	Anemometer at 20 ft with a runway exposure; Vegetation is agricultural or open within 1 mi radius and residential within 3 mi south and 7 mi north; Terrain is gently rolling within 1 mi radius, and within 10 mi radius is flat to the west but hilly beginning 8-10 mi E; higher elevation of airport than surroundings results in winds 10-15 mph greater than nearby stations.
Sioux Falls, SD March 1950-Feb 1955	Foss Field Airport	43° 34′N 96° 44′W	1400 ft	47 ft	Anemometer mounted on a mast above a building; Vegetation agricultural or open within 1 mi radius except narrow wooded area ½ mi west and agricultural within 10 mi radius; Terrain flat within 1 mi radius and gently rolling within 10 mi radius.

[1]I wish to acknowledge the following individuals for providing extra information about the eight stations:
Duluth—Leonard E. Peterson, Official in Charge
Fargo—Herbert L. Monson, Meteorologist in Charge
Hibbing—Harvel G. Blain, Station Chief
International Falls—George L. Josephs, Official in Charge
Marvin C. Kline, Electronic Technician
Minneapolis-St. Paul—John V. Graff, Meteorologist in Charge
Redwood Falls—Gerald E. Fricke, Chief
Rochester—Baline W. Amann, Official in Charge
Sioux Falls—Rollin E. Mannie, Meteorolgist in Charge
David W. Olkiewicz, Supervising Meteorologist Technician

height was used because it was the approximate center of gravity of commercial aircraft at that time (29). The standard height currently used by both the World Meteorological Organization and the National Weather Service is 10 meters (32.8 feet); anemometer heights are being changed accordingly.

The record duration for the eight stations, an important factor in all meteorological data, is shown in Table 2. Although short-term wind patterns are highly variable, annual and monthly patterns of 10 years are quite stable, as discussed in the following section.

V. Analysis of the Data

A. Wind Climatology

1. Statistics of Hourly Wind Data

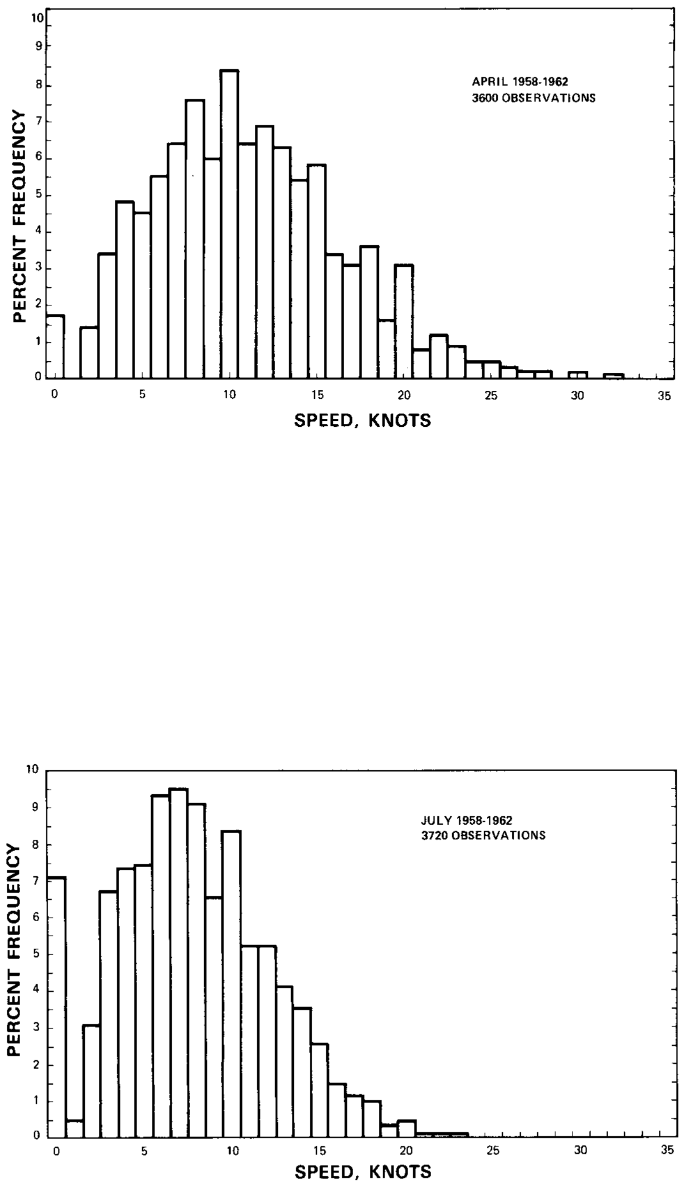
The skew typical of wind speed frequency distributions is depicted in Figure 3. As with precipitation distribution, this skew occurs because the maximum wind speed is theoretically unlimited while the minimum speed can never be less than zero. Despite this skew, it may be unwise to substitute an idealized distribution, one that can be described mathematically, for the actual wind data, as evidenced by a feature shown in Figure 3. The figure shows zero wind speed values in the distribution where none would be present in the theoretical distribution. High frequency of calm periods is most common in summertime early morning hours (Figure 4).

Takle, et al. (17) have noted a mathematical statistical function often applied to wind data is the Weibull distribution, one of the class of extreme value distributions. These researchers modified the Weibull distribution so that discrete probability of zero wind speed did occur in the density function they fitted to Iowa data.

An observational peculiarity frequently noted in meterological data is apparently present in the data shown in Figures 3 and 4. This is the tendency for observers to record 5's, 10's and their multiples more frequently than other numbers. The higher relative frequency of 10, 15, 20 and 30 knots at Minneapolis-St. Paul in April is probably evidence of this observer bias. If this apparent bias were removed and the excess frequencies reassigned to adjacent speeds the distributions in Figures 3 and 4 would be much smoother though still skewed.

There is a strong indication of bimodality in the 1500 hour April data (Figure 4) as well as observer bias in recording speeds in multiples of 5. Until data can be recorded automatically a bimodal frequency of the data cannot be determined with certainty. However, it seems reasonable to have two kinds of afternoon wind conditions: one of light winds typical of high pressure regions and the other of higher winds associated with the proximity of weather fronts and low pressure systems.

Due to observer bias in noting wind speeds there is little reason to analyze wind data in classes smaller than the Beaufort classes used in this study.



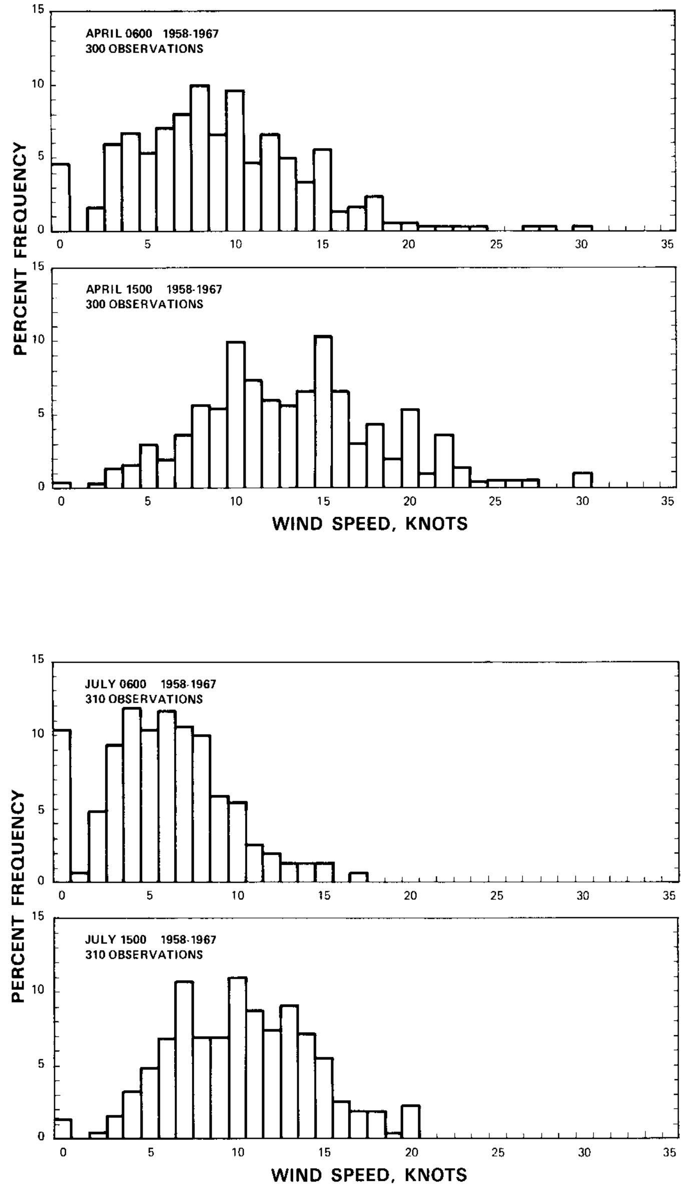


Figure 3. Frequency distribution of hourly wind speeds in April (upper) and July (lower) at Minneapolis-St. Paul, 1958-1962.

Figure 4. Frequency distribution of 0600 (6 AM) and 1500 (3 PM) wind speeds in April (upper) and July (lower) at Minneapolis-St. Paul, 1958-1962.

No information could be found indicating the length of record required for a stable frequency distribution of one minute per hour observations. This is important, since any conclusions drawn from a record of insufficient duration are questionable. A rigorous statistical test was not done on these wind data. However, using the Minneapolis-St. Paul data a comparison of the cumulative means and standard deviations of hourly values was made for generally low and high speed observation times, 0600 and 1500 hours, respectively, during generally high and low speed months, April and July, respectively. For reasons not relevant to this study the 10-year record period considered here overlaps but is not the same 10-year period used in the main body of the study.

The approach to a constant value by the cumulative means and standard deviations of April and July 0600 and 1500 hours observations is shown in Figures 5 and 6, respectively. While it is recognized that the standard deviation does not have the predictive value for skewed data that it does for normally distributed data, it remains a recognized measure of dispersion. It is apparent in Figure 5 and 6 that a 10-year observation period is

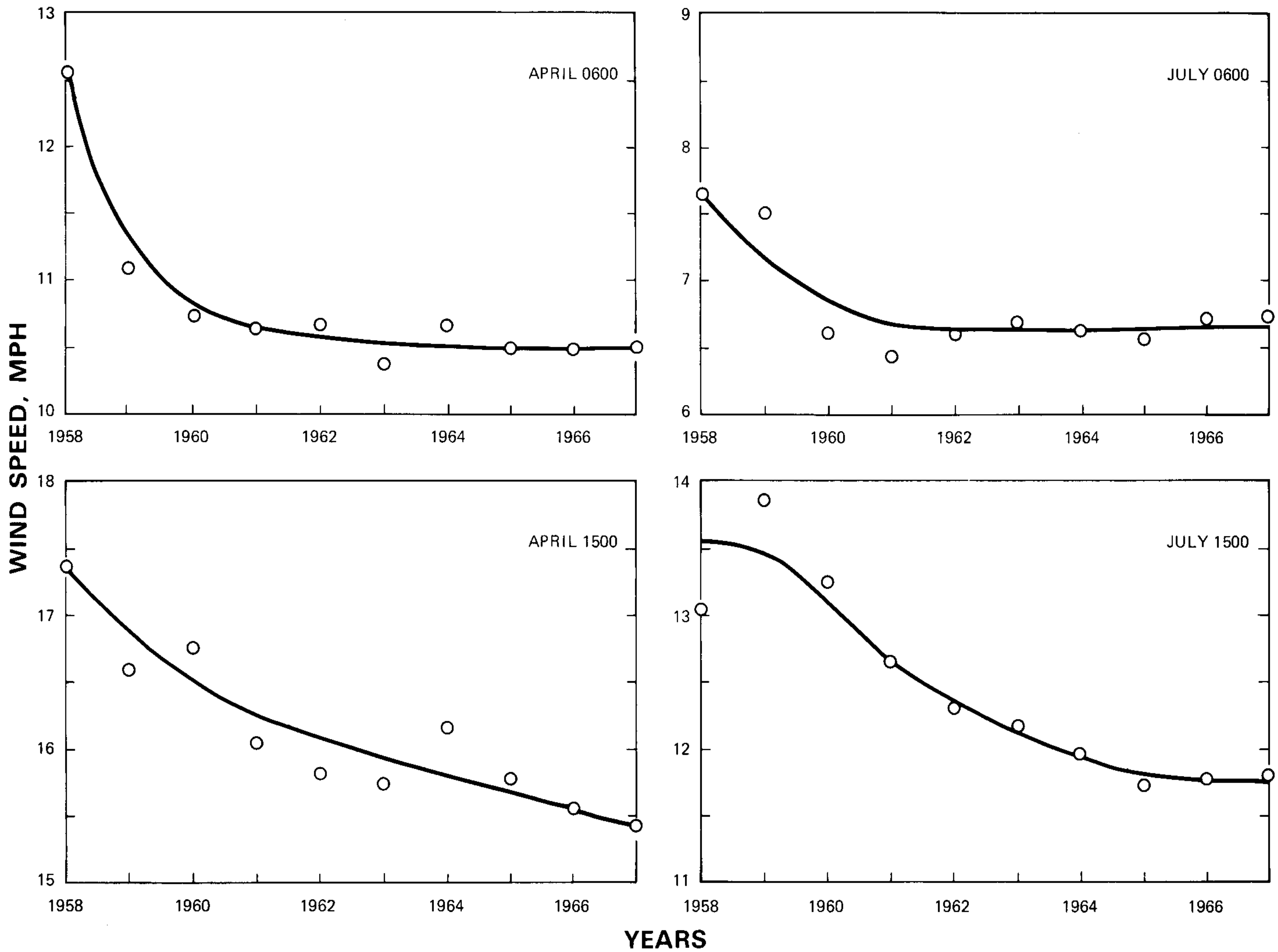


Figure 5. Cumulative mean wind speeds at 0600 (6 AM) and 1500 (3 PM) in April and July at Minneapolis-St. Paul, 1958-1967.

Table 3. Cumulative means of wind speed and the standard deviation of wind speed at Minneapolis-St. Paul in April, 1958-1962.

	Average speed, miles/hour					
Period	0600 hr	1500 hr	Day[1]	Night[2]	All day[3]	All day[4]
1958	12.6	17.4	16.3	11.7	14.0	14.0
1958-1959	11.1	16.6	15.6	10.9	13.3	13.3
1958-1960	10.7	16.7	15.6	10.8	13.2	13.2
1958-1961	10.6	16.0	15.0	10.5	12.7	12.7
1958-1962	10.7	15.8	14.8	10.7	12.8	12.7
	Standard deviation, miles/hour					
Period	0600	1500	Day[1]	Night[2]	All day[3]	All day[4]
1958	6.9	6.0	6.7	6.5	6.6	6.4
1958-1959	6.1	7.1	6.8	5.9	6.3	6.1
1958-1960	6.1	6.8	6.7	5.9	6.3	6.2
1958-1961	6.1	6.5	6.4	5.9	6.1	6.0
1958-1962	5.8	6.4	6.2	5.7	5.9	5.8

[1]0900, 1200, 1500, and 1800 hour observations
[2]2100, 0000, 0300, and 0600 hour observations
[3]0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 hour observations.
[4]All 24 hourly observations

probably of insufficient duration for a single-hour observation during the windier part of the day, such as 1500 hours. However, a record of only five to six years would be acceptable for the calmer part of the day, such as 0600 hours.

The change in means and standard deviations as the number of observations per day and per year are increased is shown in Table 3 for the month of April. This month was chosen since it usually is the month of greatest variation (Figure 1). It is apparent from both Table 3 and Figure 6 that with 24 hourly observations per day a stable distribution probably requires more than five years but less than 10.

2. Prevailing Winds and Wind Roses

Wind data can be summarized in a number of ways. One is to list the prevailing wind—the direction from which the wind most frequently blows—for a given period. Table 4 provides an example of this method. An analysis of *hourly* measurements of wind direction at St. Paul for the 15-year period 1891-1905 (28) verifies the

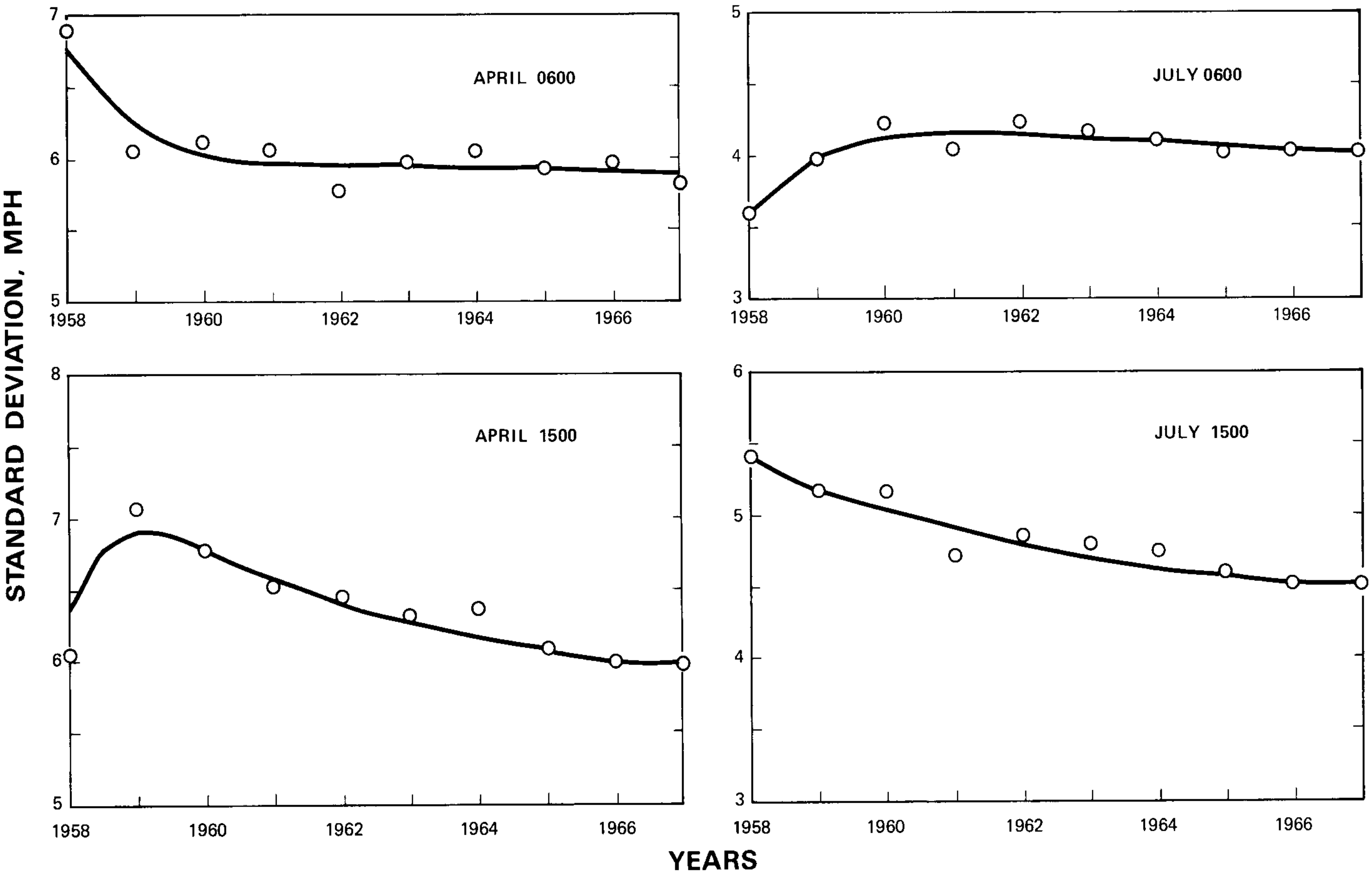


Figure 6. Cumulative standard deviations of wind speeds at 0600 (6 AM) and 1500 (3 PM) in April and July at Minneapolis-St. Paul, 1958-1967.

Minneapolis-St. Paul data in Table 4 and points to the consistency of wind direction on a climatological basis. That analysis also emphasizes that there are virtually only two directions of prevailing winds in the Twin City area and, indeed over much of Minnesota: northwest and southeast. The growing season usually starts, with some obvious exceptions at Duluth, Redwood Falls, and Sioux Falls, when southerly winds prevail. And, except for Rochester, and again Duluth, the growing season ends with the return of prevailing northwesterly winds. Duluth is a special case due to the proximity of Lake Superior.

Another, more descriptive method of summarizing data is termed a "wind rose." This is a diagram that shows how frequently the wind blows from different directions. Wind speed is not always a part of a wind rose; for this reason the wind rose can be most deceiving. For example, a wind of 5 mi/hr for one hour may be recorded in exactly the same way as a 25 mi/hr wind for the same duration.

Table 4. Monthly prevailing winds.

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Duluth	NW	NW	NW	NW	E	E	WNW	E	W	WNW	NW	NW
Fargo	NNW	NNW	NNW	NNW	NNW	SSE	SSE	SSE	SSE	SSE	NNW	NNW
Hibbing[1]	NNW	NNW	N	N	N	S	S	S	S	S	NW	NW
Int'l Falls	W	W	N	N	N	S	S	S	S	S	W	W
Mpls-St. Paul	NW	NW	NW	NW	SE	SE	SE	SE	S	SE	NW	NW
St. Paul (1891-1905)[1]	NW	NW	NW	NW	SE	SE	SE	SE[2]	SE	SE	SE[2]	NW
Redw'd Falls	NW	NW	NW	NW	NW	S	S	S	SSE	NW	NW	NW
Rochester	NW	NW	NW	S	S	S	S	S	S	S	S	S
Sioux Falls	NW	NW	NW	NW[3]	NE	S	S	S[4]	S	S	NW	NW

[1]Reference 28
[2]NW occurred with equal frequency
[3]NNW occurred with equal frequency
[4]SSE occurred with equal frequency

The wind roses shown in Figures 7-14 are limited to winds of at least 8 mi/hr. This limitation was made because most wind power systems used have a "cut-in" wind speed of about 10 mi/hr. The 8 mi/hr minimum used for the wind roses was selected because the nearest wind speed class matching the general wind generator threshold is the 8-12 mi/hr range. For example, Malver (11) lists a range of cut-in speeds of 7 to 11.4 mi/hr for one- and two-blade wind turbine generators of three different manufacturers. Reed et al. (14) have noted that unless winds are greater that 10 mi/hr for an appreciable percentage of time, a wind power system may not be practical.

The annual wind roses of all stations (Figure 7-14) display a bimodal frequency of wind directions. Except at Duluth, the most frequently occurring direction is from the northwest to north followed by winds from the south to southeast.

Station differences are as important and interesting as their common features. An obvious difference occurs at Duluth where the high frequency winds are easterly rather than southerly. Undoubtedly this is a lake effect and apparently also a topographic effect. Another difference is the higher total frequency of winds of 8 mi/hr or greater at the three western stations: Fargo, Redwood Falls, and Sioux Falls. This can be attributed in part to local effects such as instrument exposure, but is more likely related to topography. The smoother the surface the less the friction of the earth's surface reduces wind speed (Figure 2). As a result the faster winds reach closer to the surface. Of the eight stations, Fargo is the one surrounded by the greatest expanse of nearly flat terrain. It is located in the Red River Valley, one of the largest areas of nearly flat land in the world.

In the mean annual wind roses of five of the seven stations the southerly winds are approximately equal in frequency to the northerly winds. However, at Hibbing particularly, but also at International Falls, northerly winds are more frequent than the southerly winds. Duluth was not counted as it is considered a special case due to the effect of Lake Superior.

The lake breeze, which blows from water to land, occurs when the land is warmer than the water. Thus, when the lake breeze occurs, Minnesota stations along the margin of Lake Superior have easterly winds since they lie west of Lake Superior. Data in Table 5 indicate that the land is warmer than the lake from April through August. The January through March temperatures are omitted from Table 5 since the lake is usually ice covered then. The wind roses for Duluth, Figure 7, and the prevailing winds, Table 4, show that easterly winds prevail in May, June, and August and are second in frequency in April and July. In April occasional late winters with longer than normal snow cover can delay the warming of the land, thus disrupting the tendency for an easterly wind. It is not clear why east winds fail to prevail in July.

In contrast, when the water is warmer than the land the so-called land breeze develops and the wind blows from the land to the water. The Duluth wind roses, Figure 7, indicate that September and October are essentially transition months between the summer lake breeze and the land breeze. In November and December, when the land is appreciably cooler than the water, as shown in Table 5, the land breeze is induced and easterly winds are nearly absent from the wind roses. Due to the position of Minnesota stations relative to Lake Superior it is difficult to separate the land breeze effect of west to east winds from the generally prevailing westerly winds.

In winter, when much of the lake surface is frozen, there is essentially no difference between land and lake temperature and, except for the influence of local topographic differences, the Duluth and the lake shore wind patterns are similar to those in the rest of the state, with northwesterly winds dominating. The lake and land breeze circulations are relatively weak and disappear in the presence of macro-scale systems of moderate to strong winds, associated principally with the regional migratory cyclonic storms. Such systems ordinarily are most intense in late autumn and in spring, but they can eliminate the lake and land breeze effect at any time. Because the migratory systems, particularly the cyclonic storms, do not occur as frequently as the lake and land breeze circulations from April through December, they do not obscure the lake effect on a climatological basis.

The monthly mean wind roses at all stations give evidence of a seasonal wind shift of varying degrees. Such a seasonal change in the predominant wind direction is termed a monsoon. The word monsoon does not, as usually believed, refer to a rainy period. This misconception arose because the rainy period in India, where the monsoon effect is perhaps best known, is the result of the shift from dry northerly winds of the continental interior to moisture-bearing, southerly winds from the Indian ocean. In Minnesota the prevailing wind, (the direction of maximum frequency) is north-northwest in the winter switching to south-southeast in the summer. Most stations also record a one-month transition period in the spring and autumn. The Minneapolis-St. Paul monthly wind roses provide the best exhibit of the monsoon effect: north-northwest winds from November through April and south-southeast winds from June through September, with May and October as transition months.

Prevailing wind patterns at other stations vary somewhat. At Rochester the prevailing wind is southerly from April through October, without a clearly evident full-month transition period. At Duluth the prevailing winds in May, June, and August are from the east rather than the south, the lake effect. At Fargo the wind directions are essentially from the north or south, with south to south-southeast winds very frequent throughout the year.

At Hibbing and International Falls, however, a seasonal wind shift is not apparent. Instead of a prevailing south wind during the growing season, the wind roses show simply a decrease in the north-northwest winds. Also, the frequency of winds of at least 8 mi/hr is lower than at other stations, particularly in May through

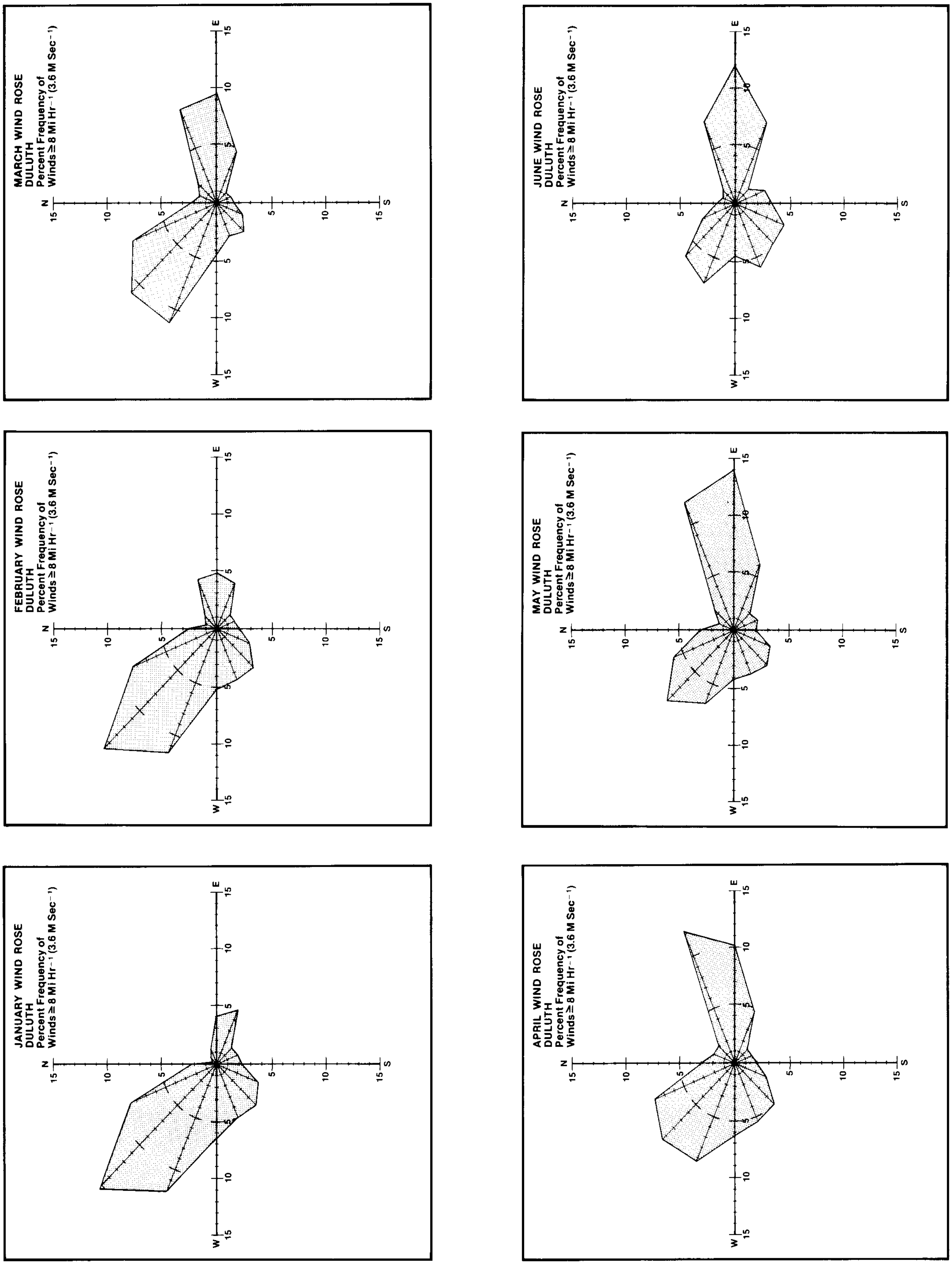
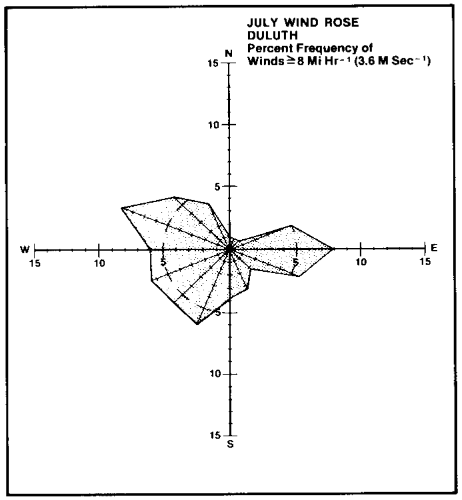
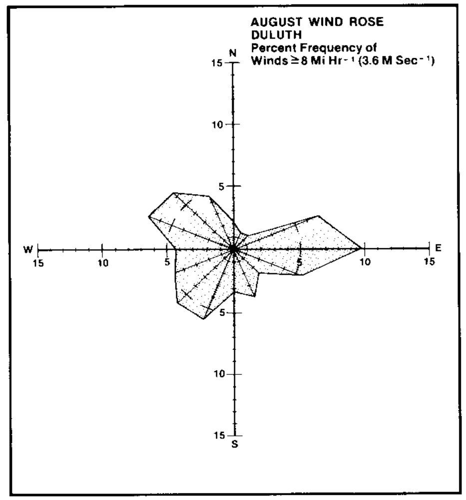


Figure 7. Monthly and annual wind roses at Duluth for winds of at least 8 mi/hr.


JULY WIND ROSE
DULUTH
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
E
W
5
10
15


AUGUST WIND ROSE
DULUTH
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
E
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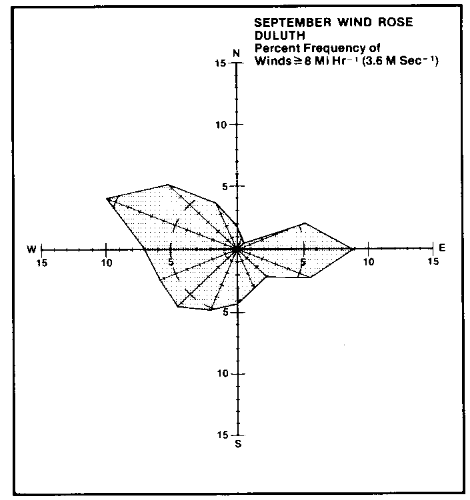
10
15


SEPTEMBER WIND ROSE
DULUTH
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
E
W
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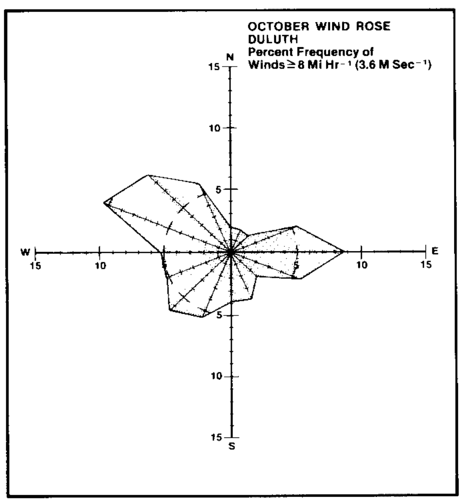
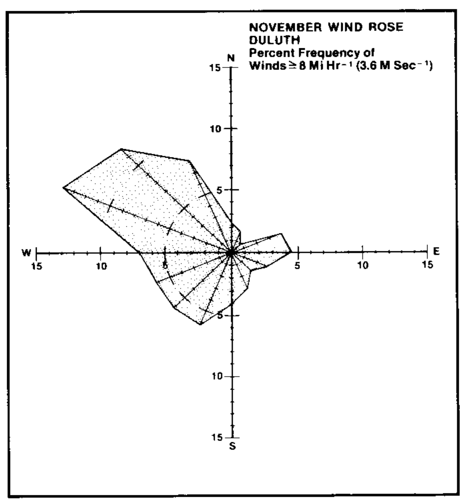
10
15


OCTOBER WIND ROSE
DULUTH
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
E
W
5
10
15


NOVEMBER WIND ROSE
DULUTH
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
E
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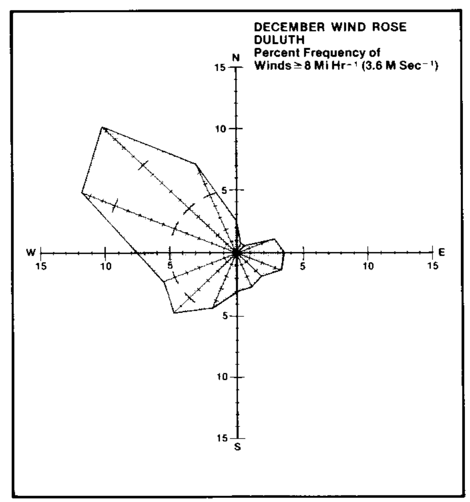
15


DECEMBER WIND ROSE
DULUTH
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
E
W
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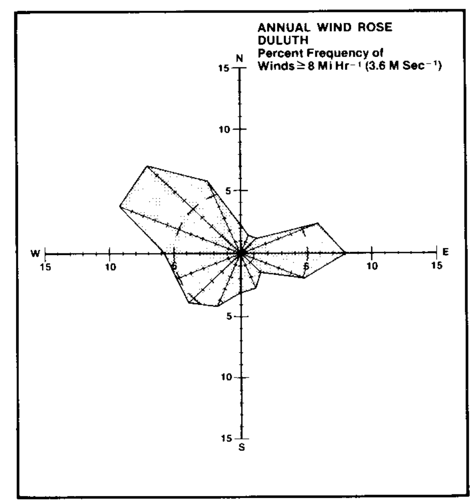
10
15


ANNUAL WIND ROSE
DULUTH
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
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W
5
10
15

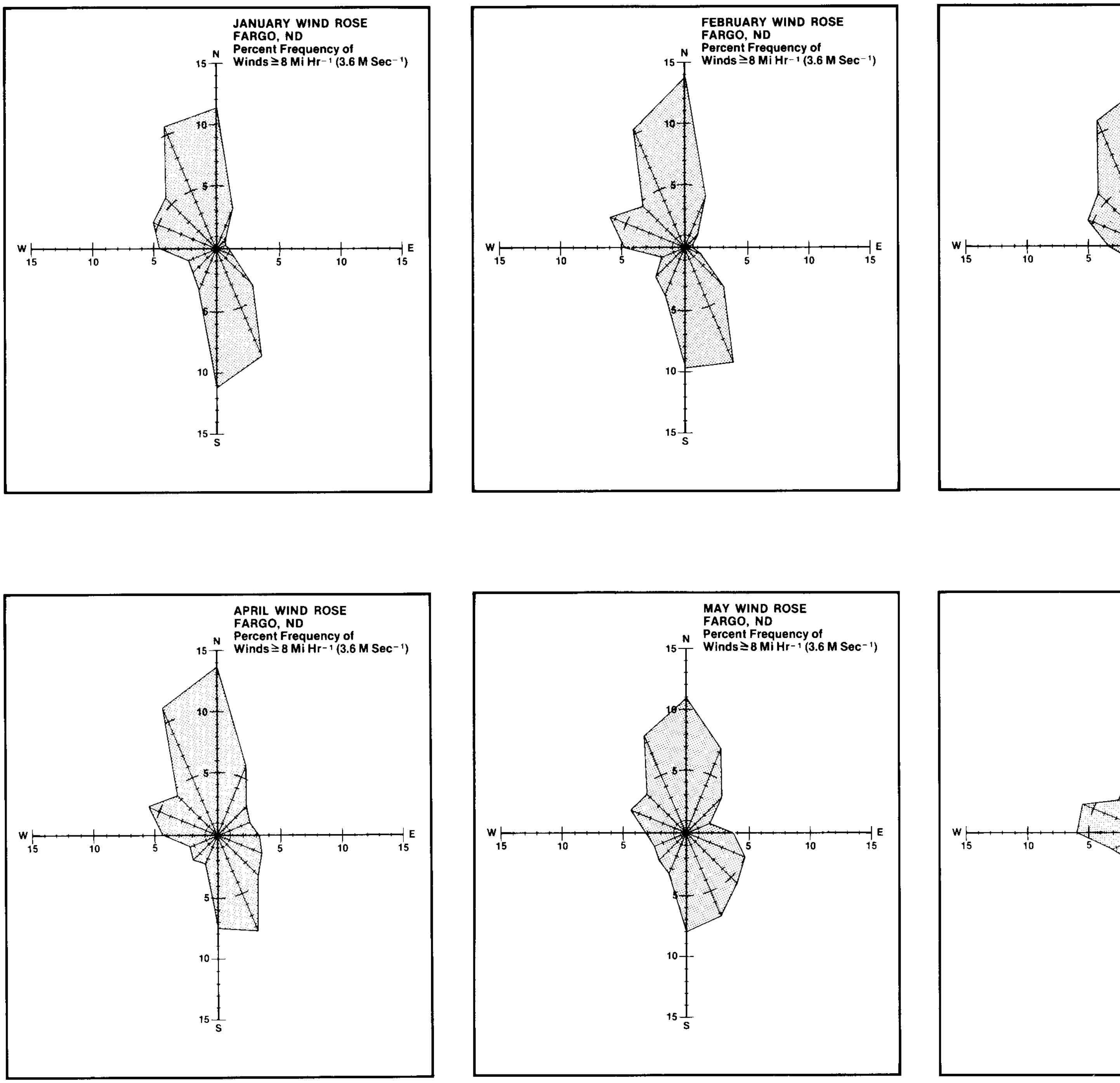
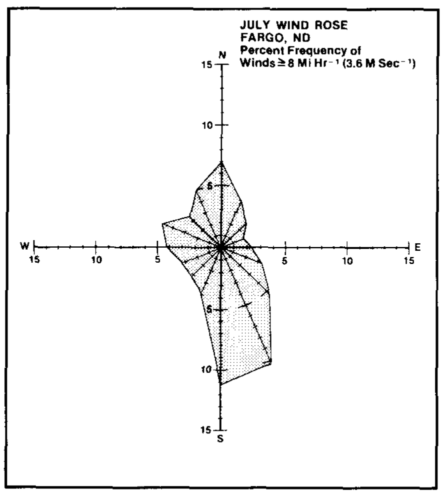
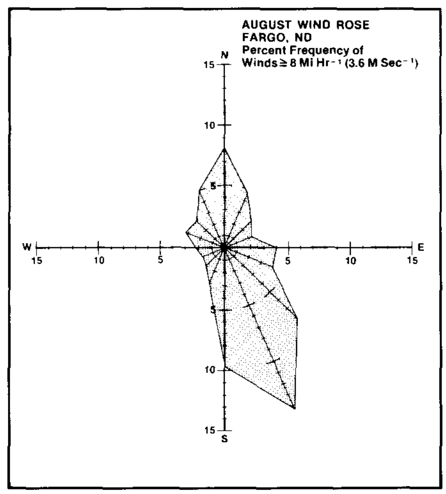
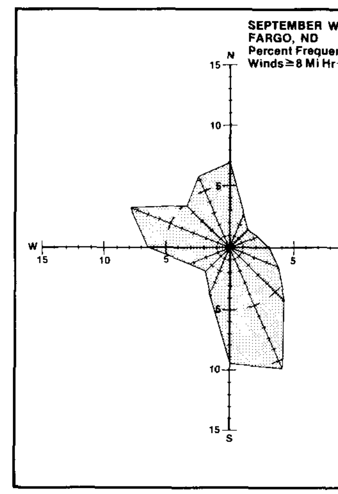
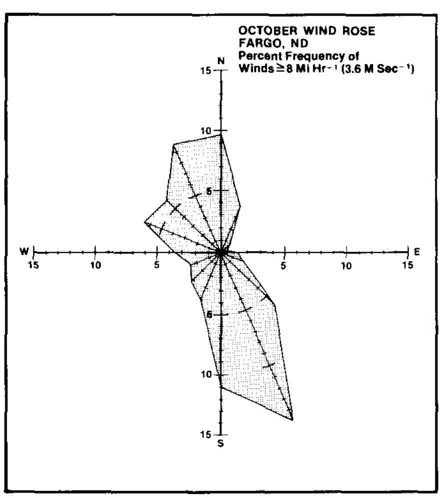


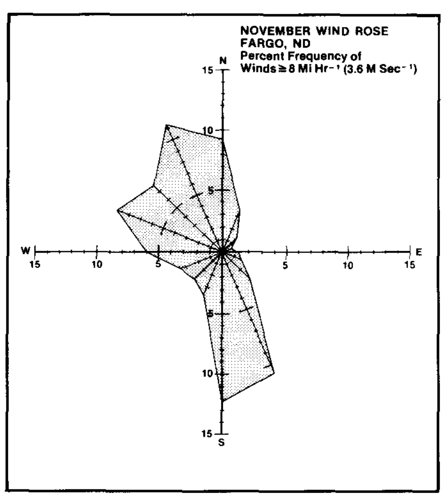
Figure 8. Monthly and annual wind roses at Fargo for winds of at least 8 mi/hr.

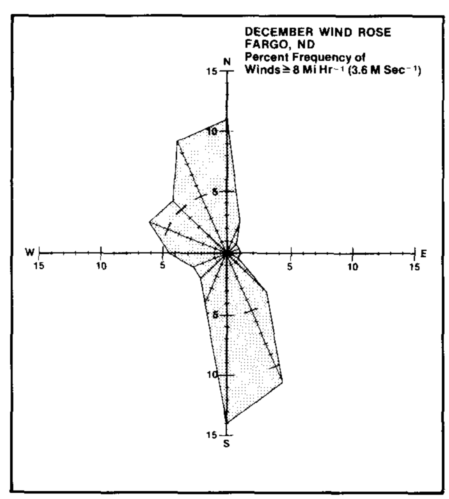

JULY WIND ROSE
FARGO, ND
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E

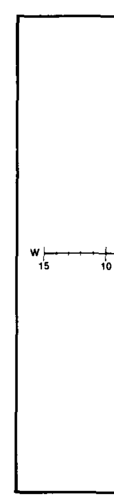

AUGUST WIND ROSE
FARGO, ND
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E


SEPTEMBER W
FARGO, ND
Percent Frequen
Winds ≥ 8 Mi Hr
N
S
W


OCTOBER WIND ROSE
FARGO, ND
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E


NOVEMBER WIND ROSE
FARGO, ND
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E


DECEMBER WIND ROSE
FARGO, ND
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E



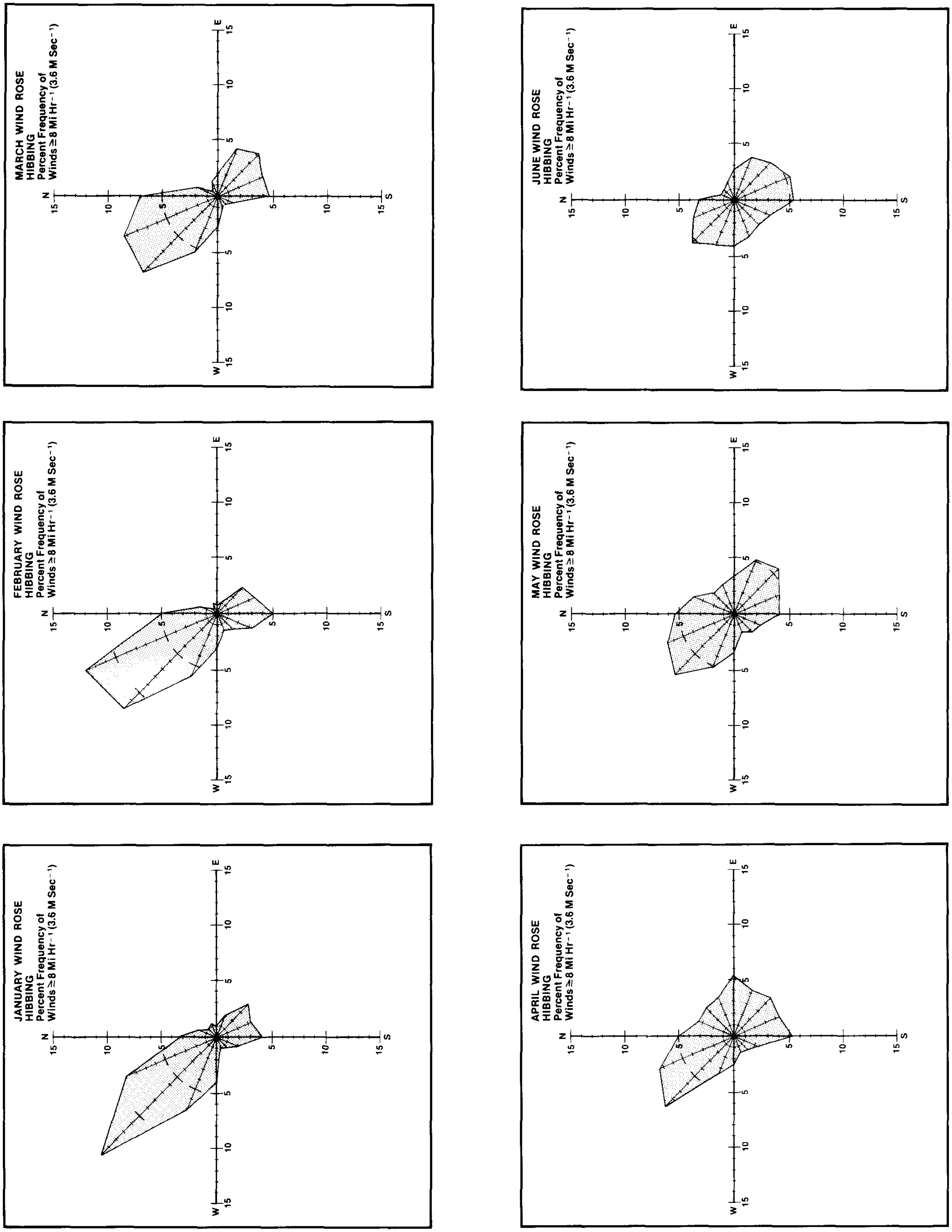
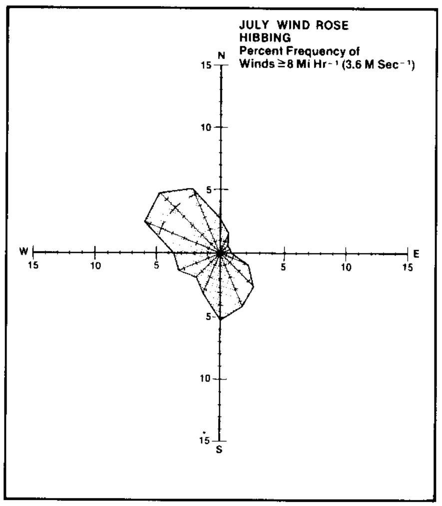


Figure 9. Monthly and annual wind roses at Hibbing for winds of at least 8 mi/hr.


JULY WIND ROSE
HIBBING
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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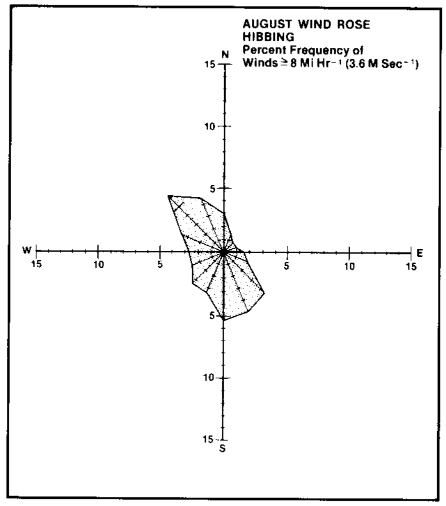
AUGUST WIND ROSE
HIBBING
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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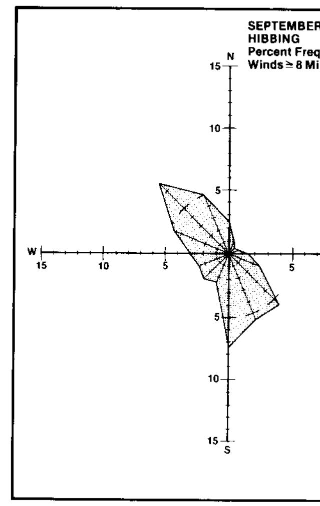
SEPTEMBER
HIBBING
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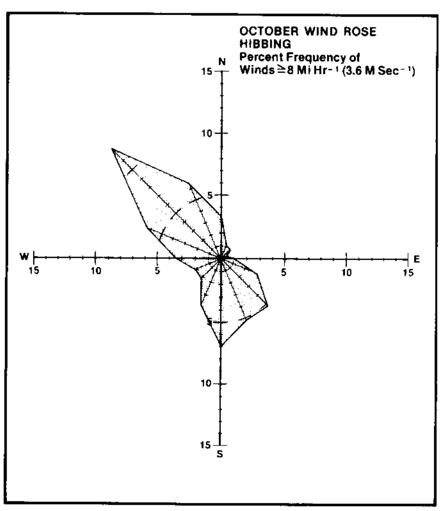
OCTOBER WIND ROSE
HIBBING
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
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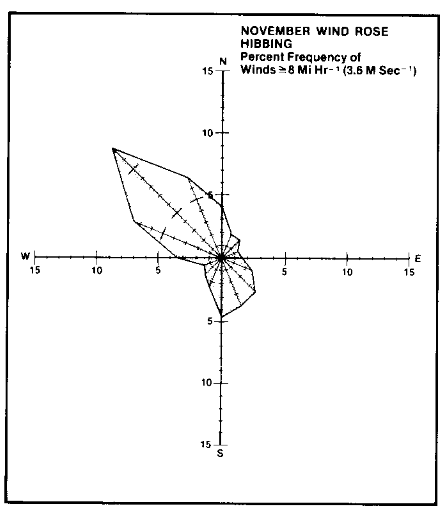
NOVEMBER WIND ROSE
HIBBING
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
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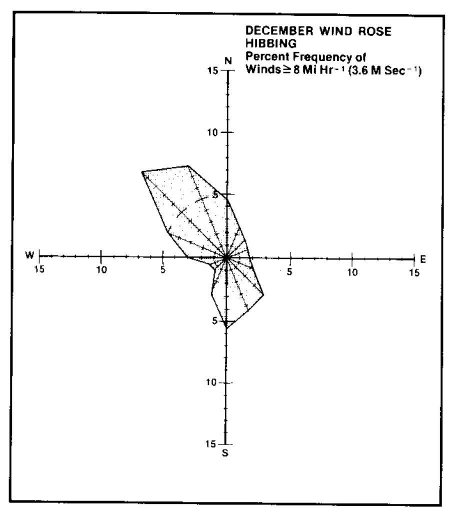
DECEMBER WIND ROSE
HIBBING
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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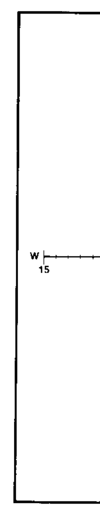
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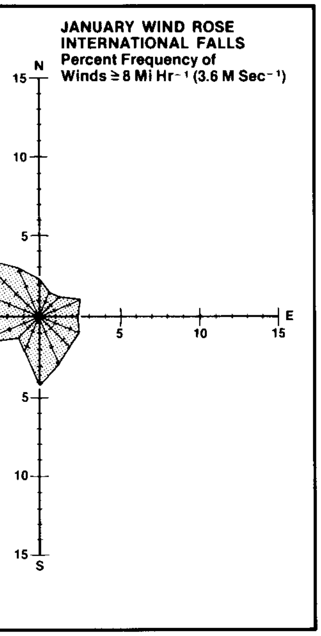
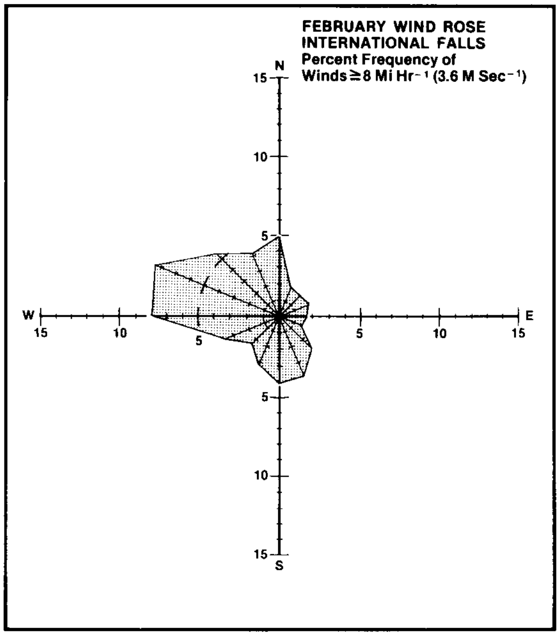
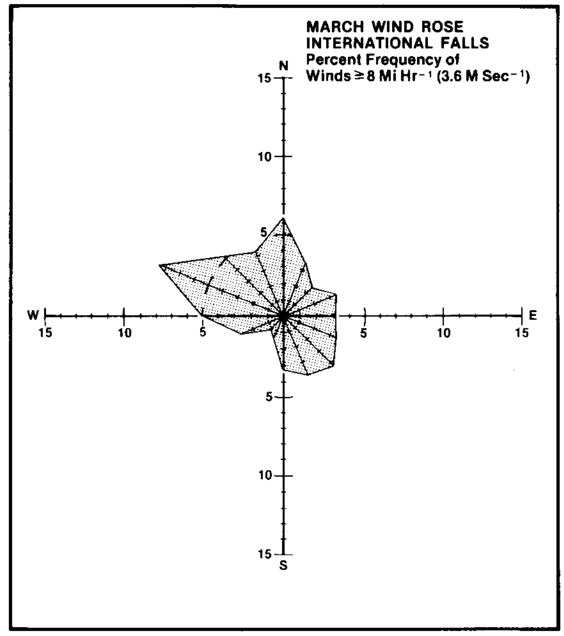


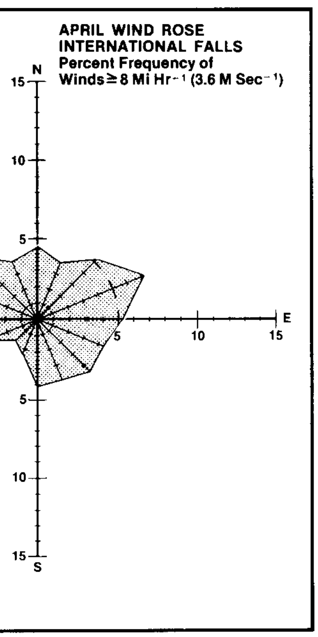
JANUARY WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr^{-1} (3.6 M Sec^{-1})



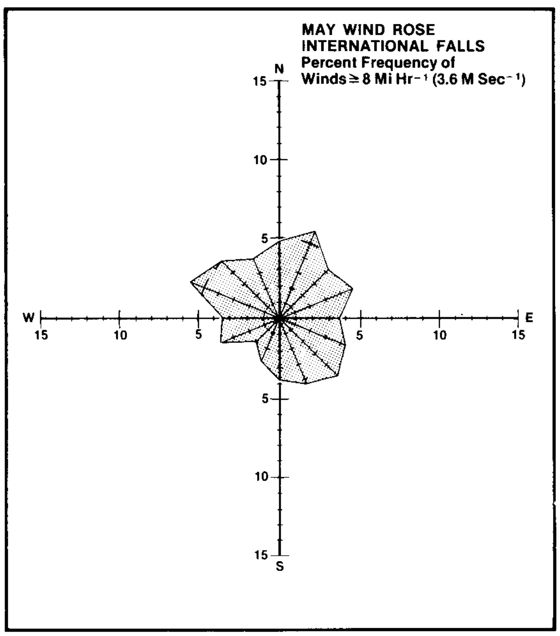
FEBRUARY WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr^{-1} (3.6 M Sec^{-1})



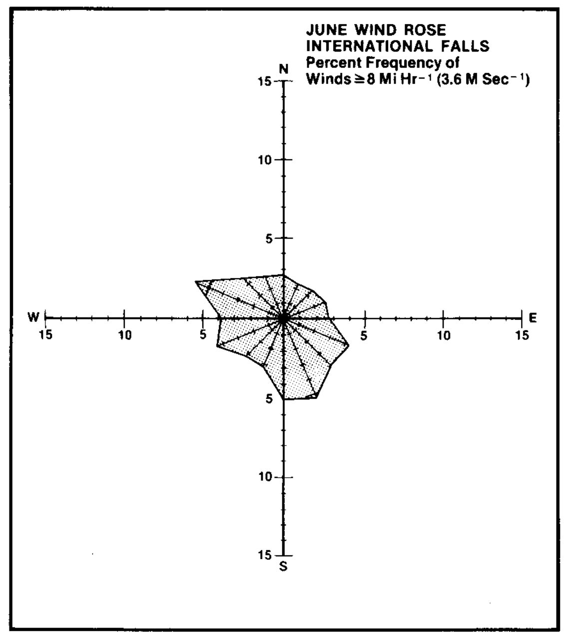
MARCH WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr^{-1} (3.6 M Sec^{-1})



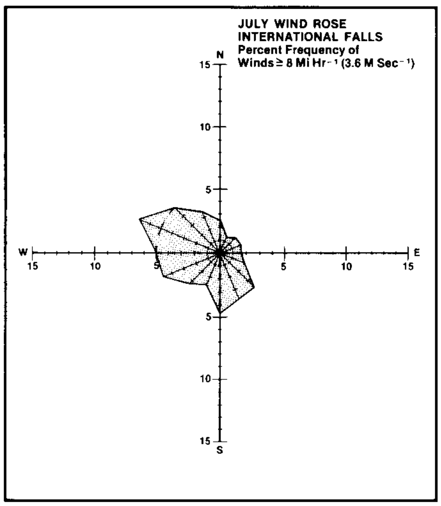
APRIL WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr^{-1} (3.6 M Sec^{-1})



MAY WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr^{-1} (3.6 M Sec^{-1})



JUNE WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr^{-1} (3.6 M Sec^{-1})


JULY WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
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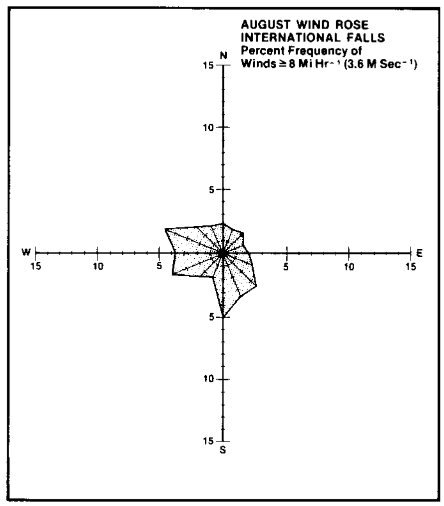
5


AUGUST WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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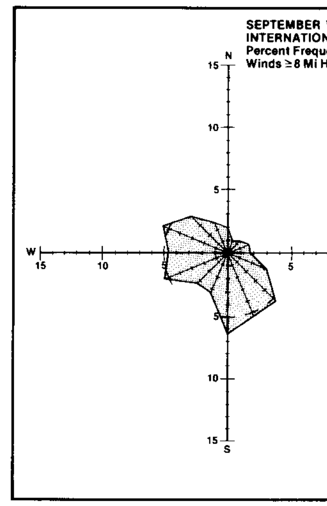
SEPTEMBER
INTERNATION
Percent Frequ
Winds ≥ 8 Mi H
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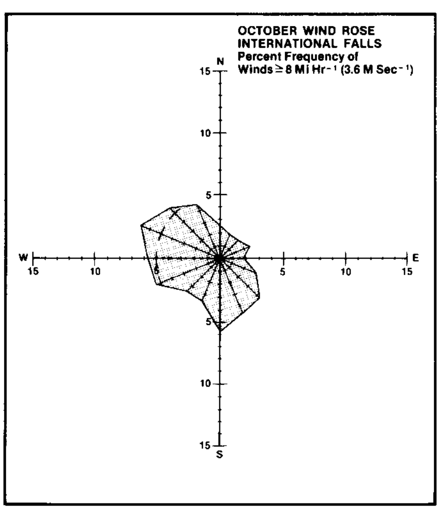
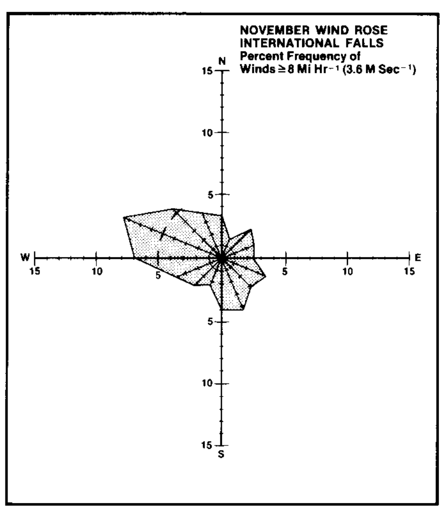

OCTOBER WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
10
5


NOVEMBER WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
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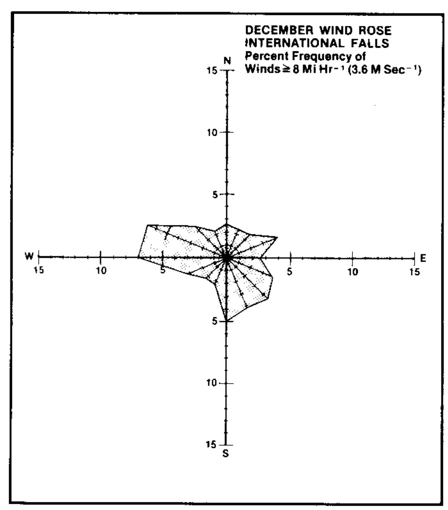
5


DECEMBER WIND ROSE
INTERNATIONAL FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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W
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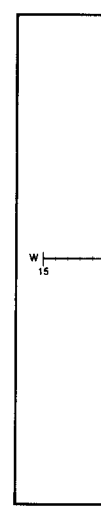

W
15

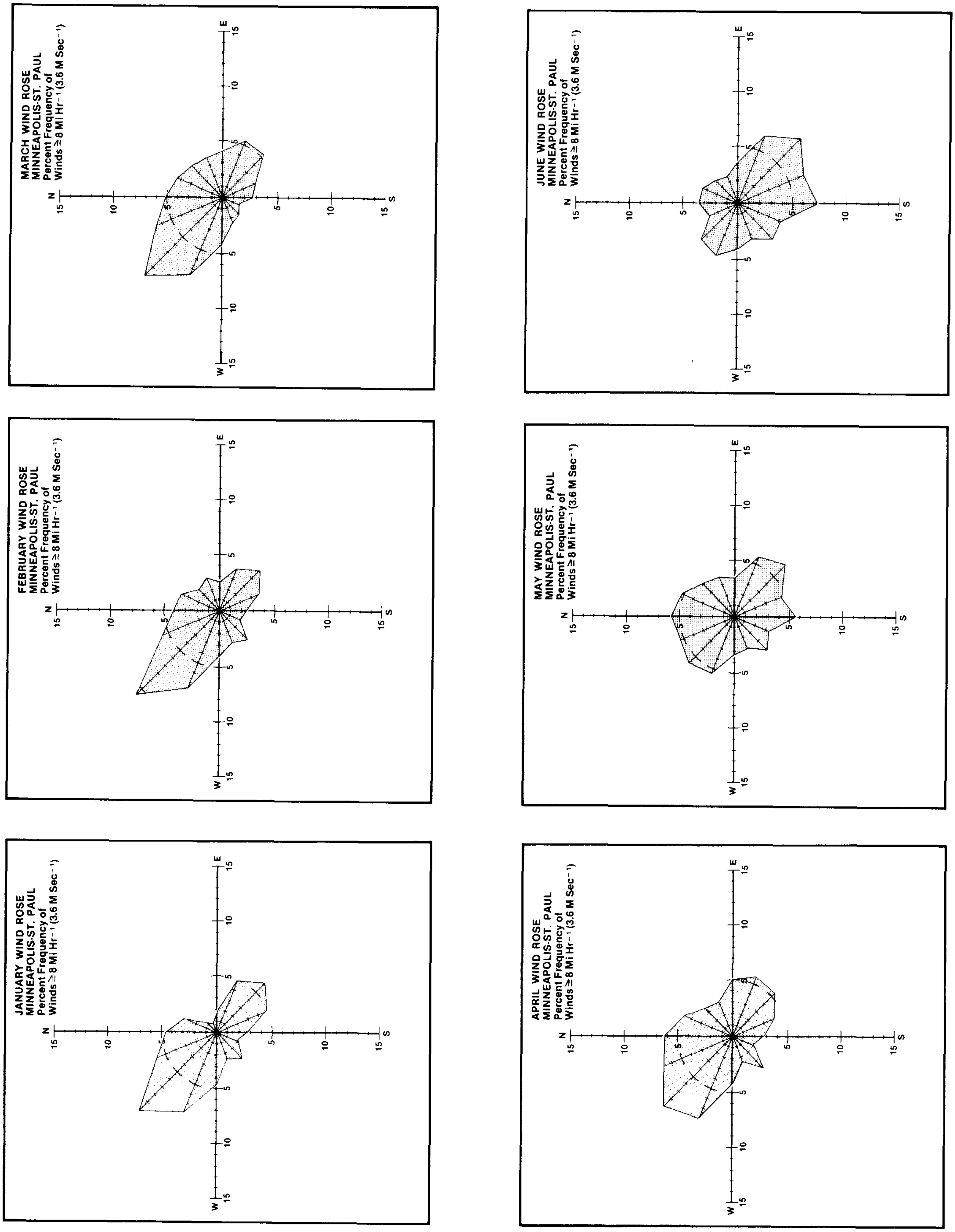
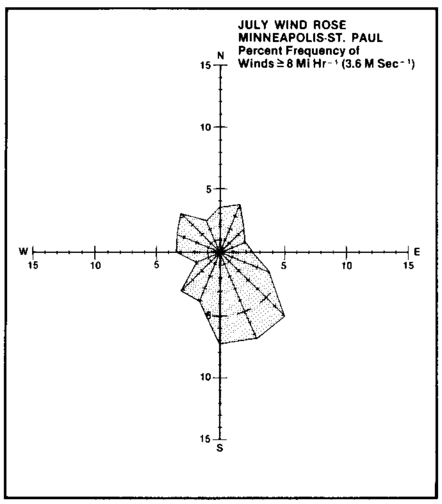
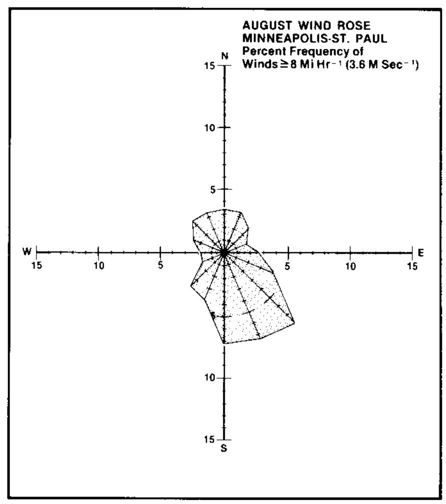
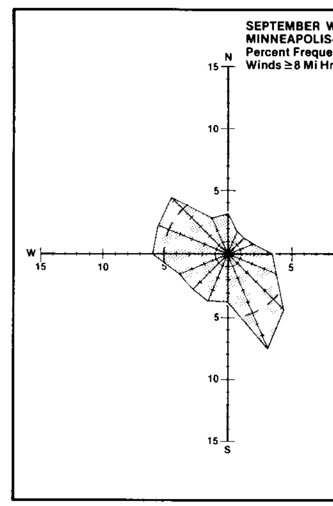


Figure 11. Monthly and annual wind roses at Minneapolis-St. Paul for winds of at least 8 mi/hr.


JULY WIND ROSE
MINNEAPOLIS-ST. PAUL
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
10
5


AUGUST WIND ROSE
MINNEAPOLIS-ST. PAUL
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
10
5


SEPTEMBER W
MINNEAPOLIS-
Percent Freque
Winds ≥ 8 Mi Hr
N
S
W
15
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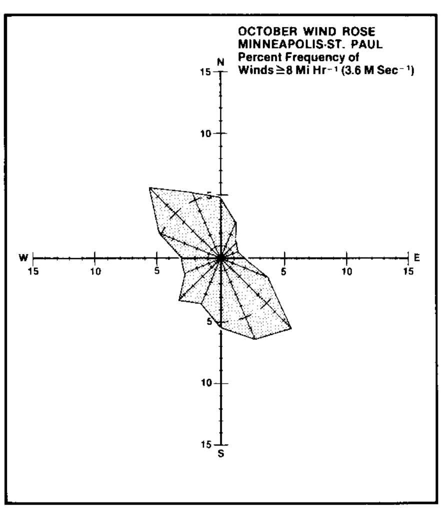
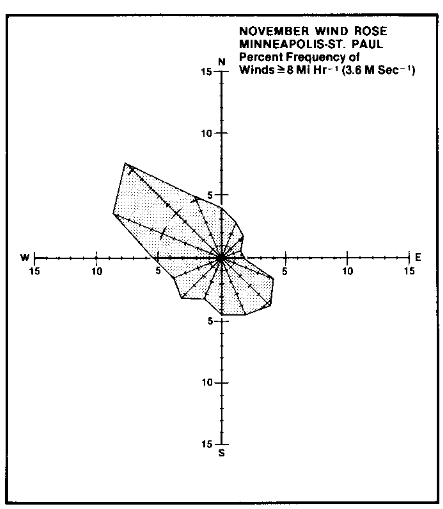
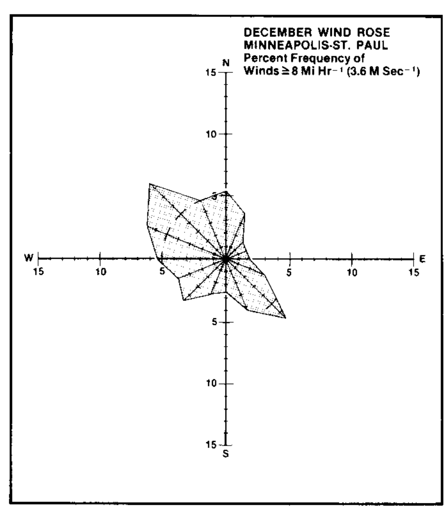
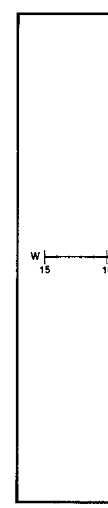
5


OCTOBER WIND ROSE
MINNEAPOLIS-ST. PAUL
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
10
5


NOVEMBER WIND ROSE
MINNEAPOLIS-ST. PAUL
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
10
5


DECEMBER WIND ROSE
MINNEAPOLIS-ST. PAUL
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
10
5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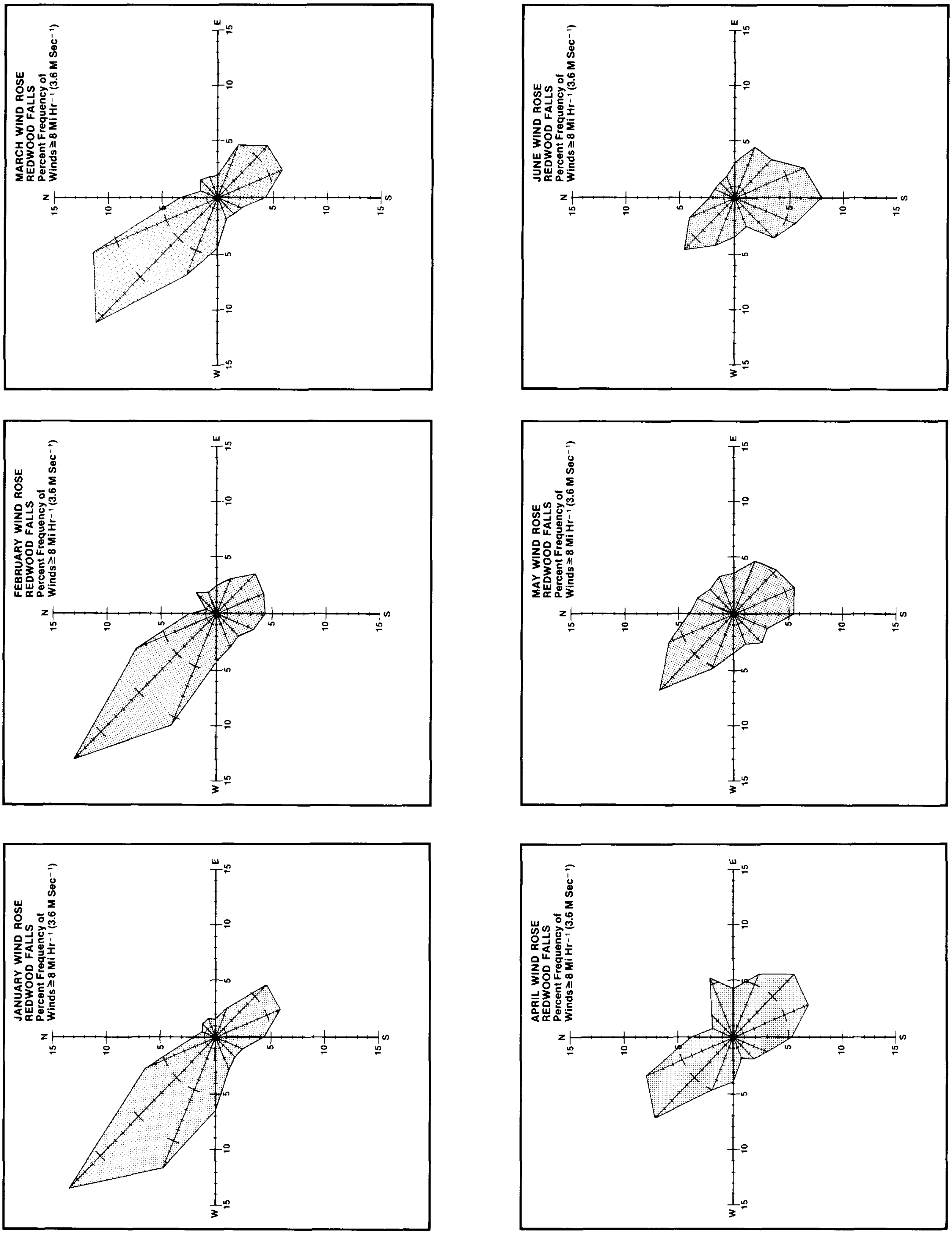
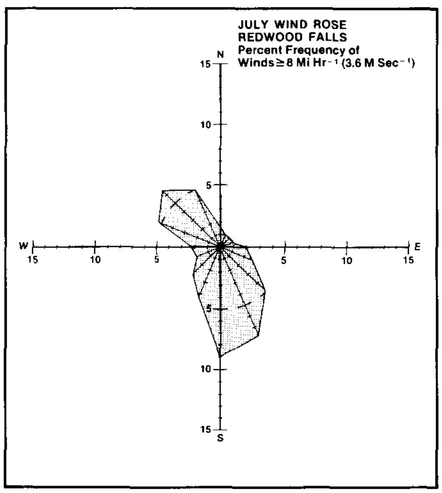


Figure 12. Monthly and annual wind roses at Redwood Falls for winds of at least 8 mi/hr.


JULY WIND ROSE
REDWOOD FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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W
E
15
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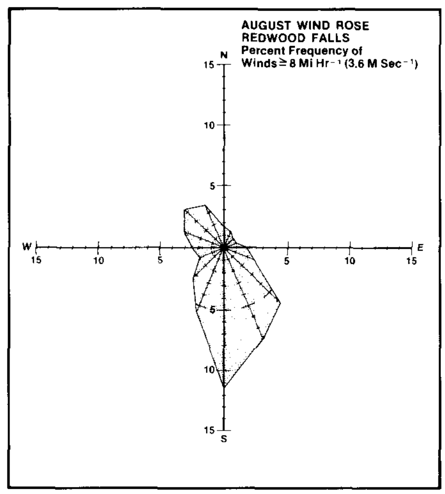
AUGUST WIND ROSE
REDWOOD FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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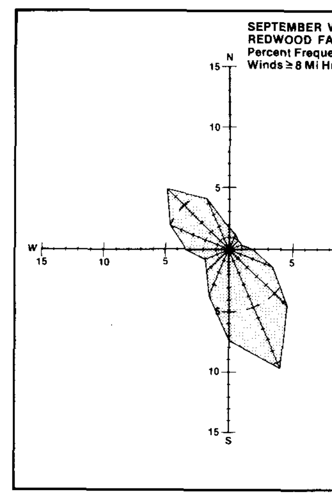
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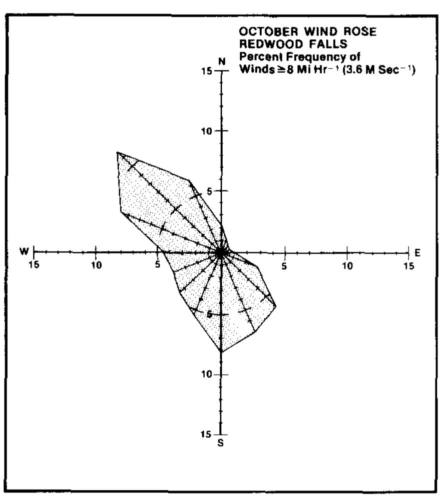
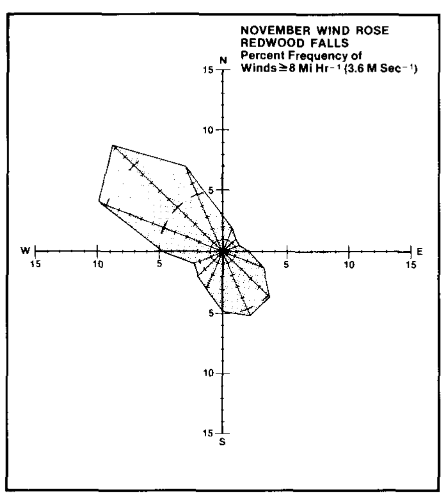

OCTOBER WIND ROSE
REDWOOD FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E
15
10
5


NOVEMBER WIND ROSE
REDWOOD FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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15
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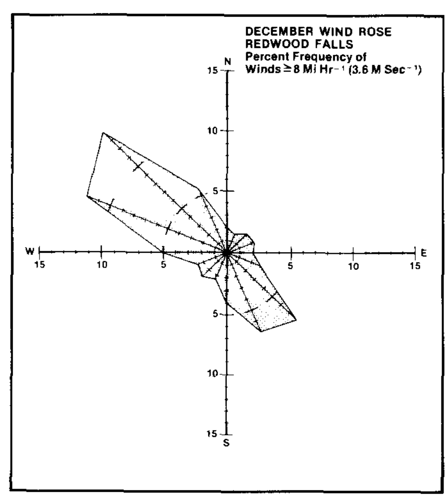
5


DECEMBER WIND ROSE
REDWOOD FALLS
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
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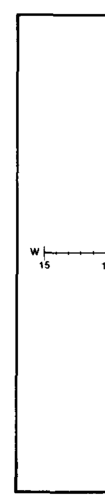
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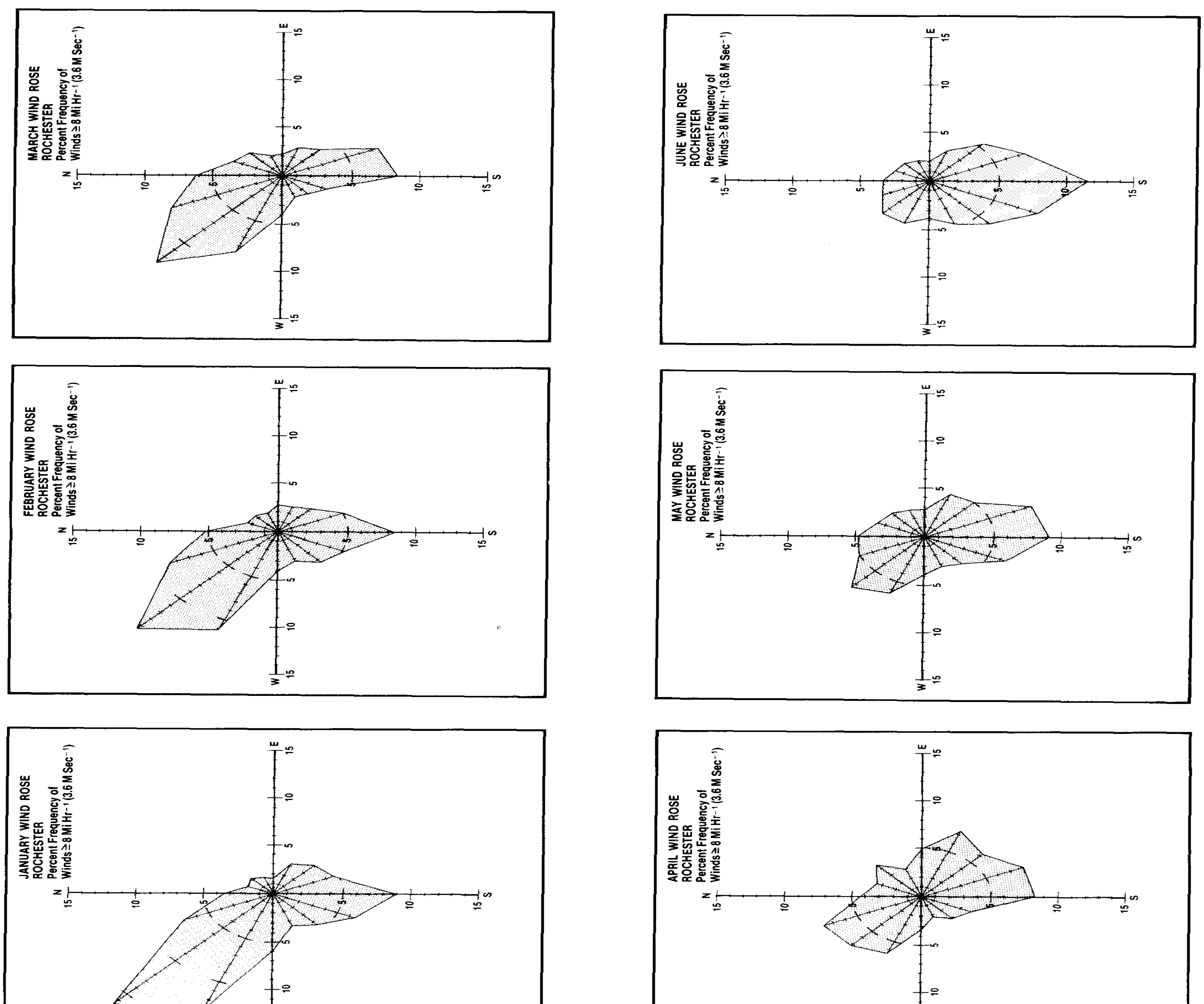
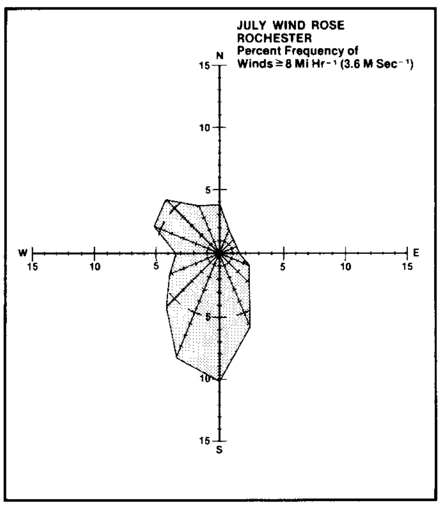
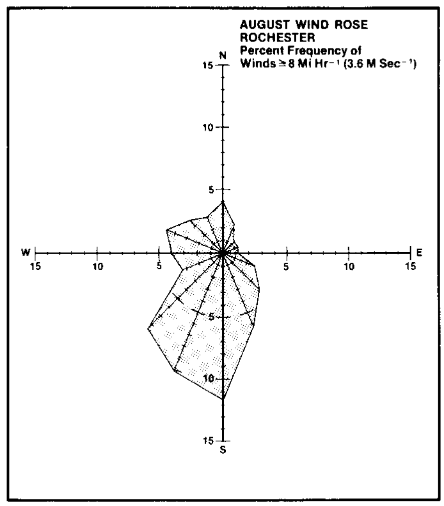
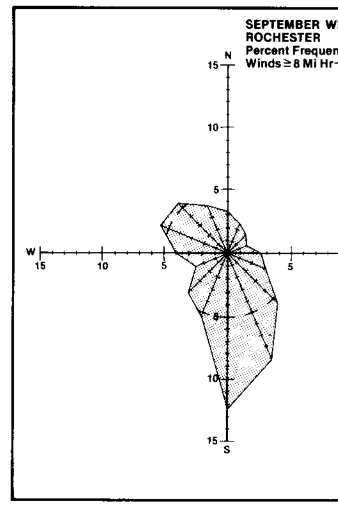


Figure 13. Monthly and annual wind roses at Rochester for winds of at least 8 mi/hr.


JULY WIND ROSE
ROCHESTER
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E


AUGUST WIND ROSE
ROCHESTER
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
E


ROCHESTER
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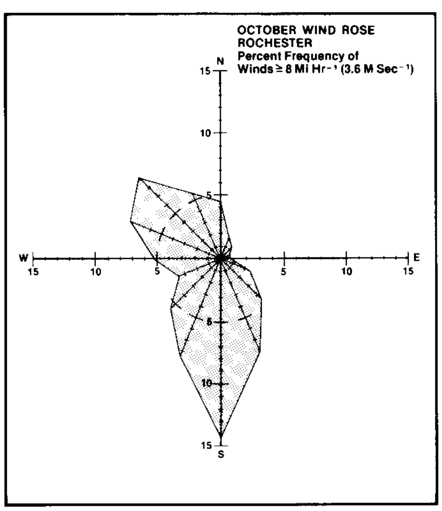
OCTOBER WIND ROSE
ROCHESTER
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
W
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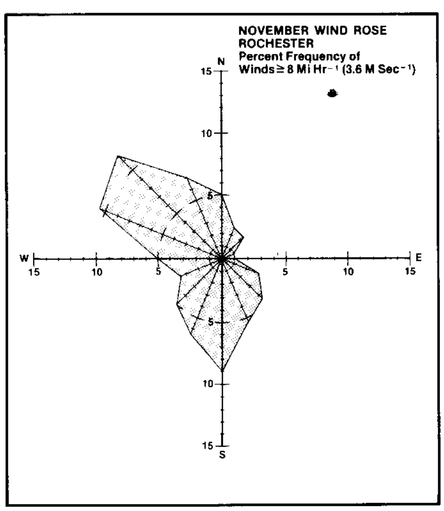
NOVEMBER WIND ROSE
ROCHESTER
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
S
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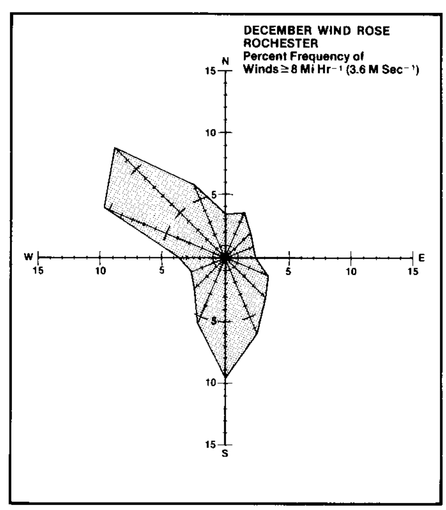
DECEMBER WIND ROSE
ROCHESTER
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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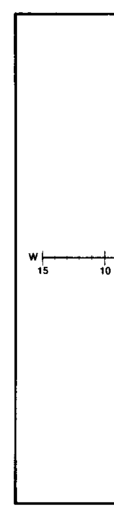
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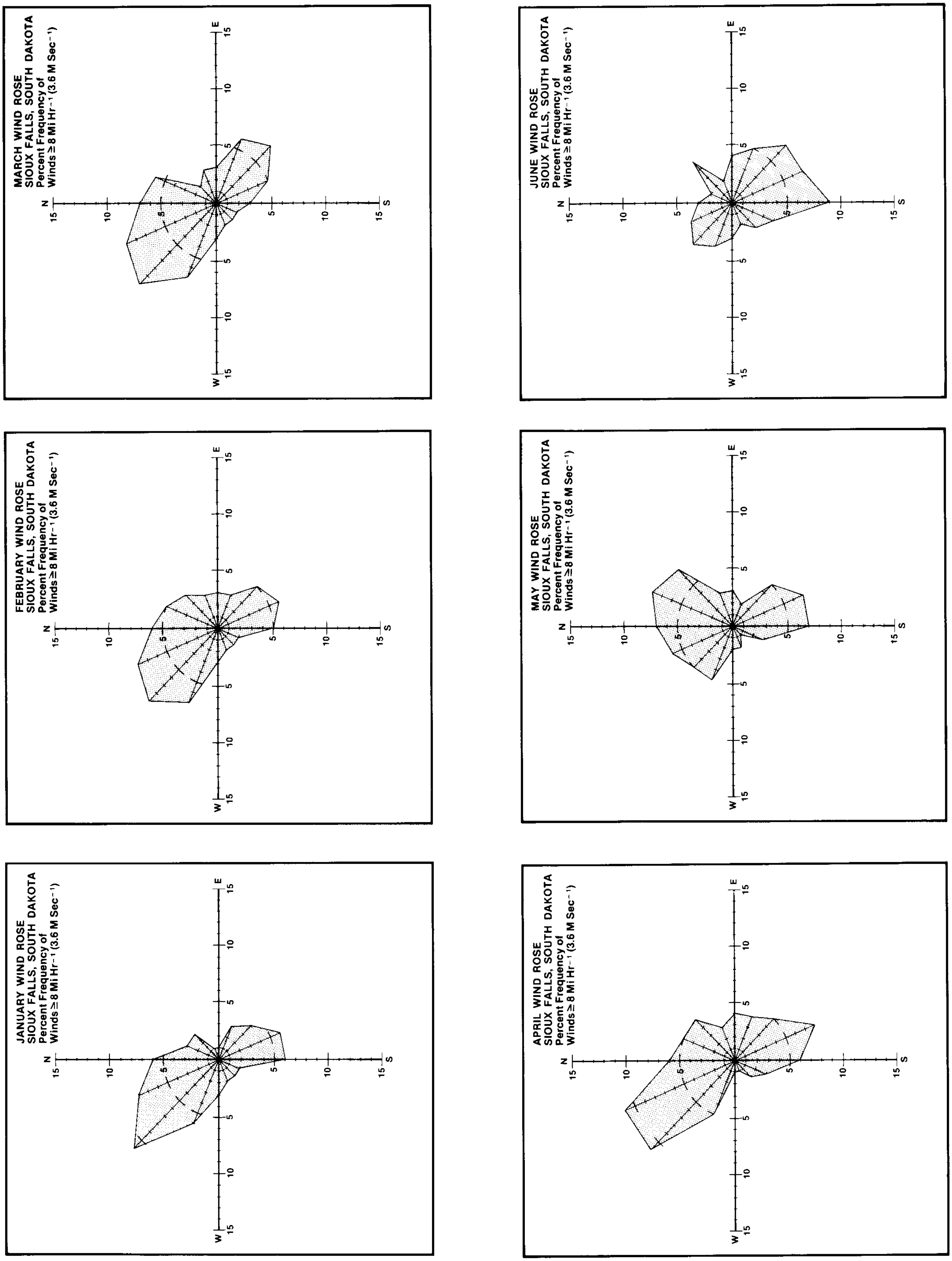
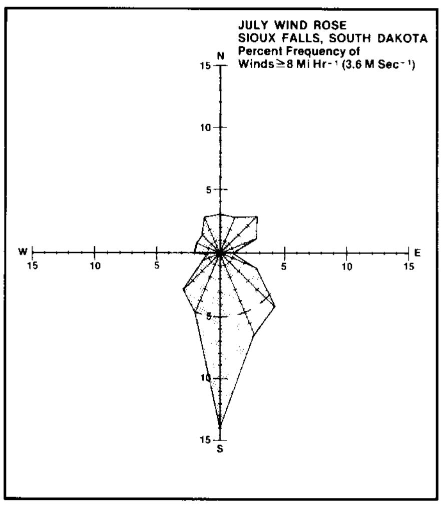


Figure 14. Monthly and annual wind roses at Sioux Falls for winds of at least 8 mi/hr.


JULY WIND ROSE
SIOUX FALLS, SOUTH DAKOTA
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
N
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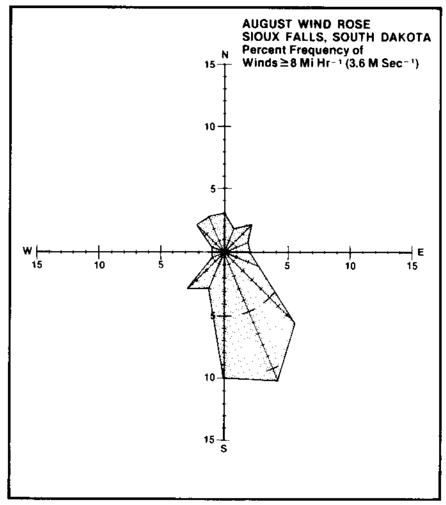
AUGUST WIND ROSE
SIOUX FALLS, SOUTH DAKOTA
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
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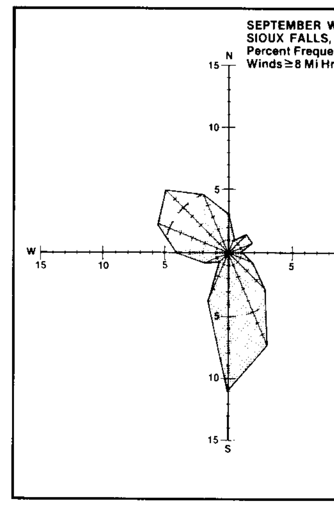
SEPTEMBER W
SIOUX FALLS,
Percent Freque
Winds ≥ 8 Mi Hr
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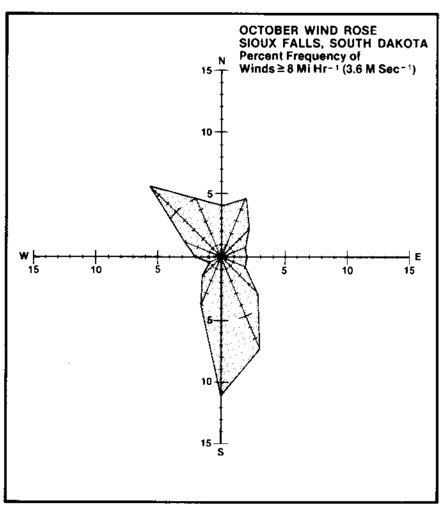
OCTOBER WIND ROSE
SIOUX FALLS, SOUTH DAKOTA
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
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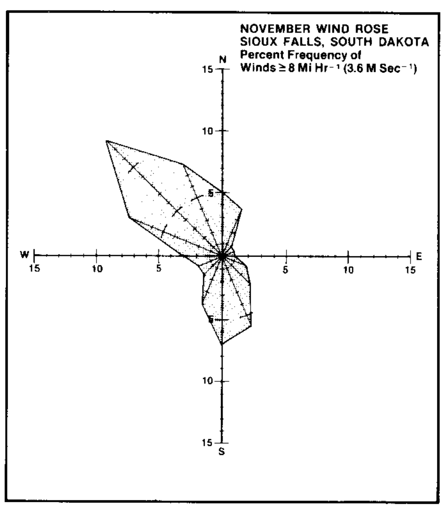
NOVEMBER WIND ROSE
SIOUX FALLS, SOUTH DAKOTA
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
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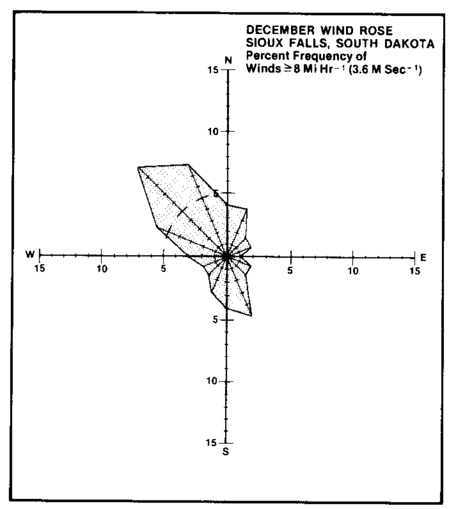
DECEMBER WIND ROSE
SIOUX FALLS, SOUTH DAKOTA
Percent Frequency of
Winds ≥ 8 Mi Hr⁻¹ (3.6 M Sec⁻¹)
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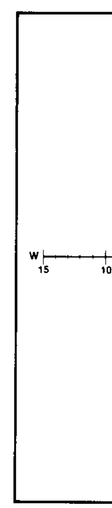
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Table 5. Temperature difference between the air and water at Duluth.[1]

	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean
Duluth	38.6	49.4	59.0	65.6	64.1	54.4	45.3	28.4	14.4	46.6
Lake Superior	35.0	36.5	39.7	48.1	56.4	55.2	47.4	41.9	38.8	44.3
Difference	3.6	12.9	19.3	17.5	7.7	–0.8	–2.1	–13.5	–24.4	2.3

[1]Air temperature normals measured at Duluth airport (27), Lake Superior mean water temperatures measured at 47.2°N and 90.8°W (22). 47.2°N and 90.8°W is located a short distance to the north and west of the Apostle Islands in Lake Superior and is along a shipping lane.

September, with a marked minimum in August at both stations. An added peculiarity at International Falls is the relatively high frequency of nearly all directions in April, May and June. April and May appear to be the spring transition months at Redwood Falls, with southerly winds prevailing during June and September and the autumn transition month in October.

3. Wind Speed Means, Variability, and Extremes

Seven stations show a monthly mean wind speed maximum in April, while Hibbing's maximum occurs in May (Tables 6-13). At Fargo and Rochester the April maximum is equalled in November and January, respectively. The wind speed minimum is found in either July or August at all stations. The higher winds of the fall and spring are associated with the proximity of the polar front.

Figure 15 shows the frequency of winds less than 8 mi/hr at the three western stations—Fargo, Redwood Falls, and Sioux Falls—and Figure 16 shows the five eastern stations. All stations except Rochester show a minimum frequency of low speeds in April and usually a weak secondary minimum in October or November. Both minima in low wind speed frequencies are associated with the proximity of the polar front, which brings warmer and usually more moist air into the state in the spring as it moves northward across the state, and cuts off the supply of warm and moist air in the fall as it moves southward. The lower January frequency of winds less than 8 mi/hr at Redwood Falls is difficult to explain. It might be due to a funneling effect of northwest flow between the Alexandria Moraine and the Coteau des Prairies (Buffalo Ridge). However, a more intensive study is needed to verify this possibility. At Rochester it is probably a higher station altitude effect.

Table 6. Monthly and annual wind parameters at Duluth.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	10.3	–6.4	295°	4.2	40.8
Feb	10.8	–1.8	305°	3.4	32.5
Mar	10.9	–0.9	344°	2.4	22.9
Apr	12.7	15.5	335°	2.3	19.1
May	11.9	8.2	26°	1.6	16.3
Jun	10.1	–8.2	207°	0.2	2.1
Jul	7.6	–30.9	244°	1.5	16.0
Aug	9.5	–13.6	156°	0.6	6.6
Sep	10.8	–1.8	251°	1.7	16.4
Oct	11.3	2.7	276°	1.7	15.7
Nov	12.4	12.7	288°	4.3	36.4
Dec	11.3	2.7	286°	4.3	39.8
Annual	11.0		297°	1.9	11.2

Table 7. Monthly and annual wind parameters at Fargo.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	11.6	–2.5	298°	1.9	17.0
Feb	11.6	–2.5	298°	1.6	14.7
Mar	12.1	1.7	338°	1.3	10.7
Apr	13.6	14.3	340°	2.4	18.2
May	12.4	4.2	0°	0.9	7.2
Jun	11.4	–4.2	198°	1.3	11.9
Jul	9.9	–16.8	182°	1.8	18.5
Aug	10.4	–12.6	143°	2.1	12.1
Sep	11.7	–1.7	231°	1.6	14.0
Oct	12.5	5.0	229°	1.9	14.6
Nov	13.6	14.3	296°	3.4	25.7
Dec	12.1	1.7	274°	2.2	18.5
Annual	11.9		280°	0.9	8.0

Table 8. Monthly and annual wind parameters at Hibbing.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	9.3	0.0	307°	3.6	33.4
Feb	9.2	–1.1	303°	3.9	35.3
Mar	9.5	2.2	299°	2.2	19.6
Apr	10.6	14.0	12°	1.7	14.7
May	10.8	16.1	348°	1.1	9.1
Jun	9.0	–3.2	218°	1.6	15.2
Jul	8.3	–10.8	265°	2.7	26.7
Aug	7.9	–15.1	254°	2.9	28.7
Sep	8.6	–7.5	227°	1.4	13.8
Oct	9.9	6.5	273°	2.7	23.9
Nov	9.5	2.2	311°	2.6	24.7
Dec	8.9	–4.3	304°	1.7	17.0
Annual	9.3		287°	2.4	25.1

Table 9. Monthly and annual wind parameters at International Falls.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	9.8	2.1	271°	2.9	28.8
Feb	9.8	2.1	279°	2.7	26.9
Mar	9.9	3.1	329°	1.4	13.2
Apr	11.1	15.6	28°	1.1	10.0
May	10.6	10.4	66°	0.4	4.1
Jun	9.4	−2.1	207°	1.4	14.7
Jul	8.7	−9.4	252°	2.5	26.8
Aug	8.2	−14.6	228°	1.5	16.3
Sep	9.2	−4.2	220°	2.4	24.5
Oct	9.9	3.1	248°	2.3	21.9
Nov	9.8	2.1	93°	1.8	18.5
Dec	9.2	−4.2	238°	1.0	10.3
Annual	9.6		258°	1.4	14.0

Table 10. Monthly and annual wind parameters at Minneapolis-St. Paul.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	8.9	−6.3	285°	1.8	20.0
Feb	9.3	−2.1	305°	1.5	16.8
Mar	9.9	4.2	349°	1.6	15.7
Apr	11.2	17.9	336°	1.4	12.9
May	10.6	11.6	109°	0.1	1.2
Jun	9.7	2.1	150°	1.3	15.4
Jul	8.4	−11.6	184°	1.6	18.3
Aug	8.1	−14.7	153°	1.9	24.0
Sep	9.3	−2.1	207°	2.0	22.1
Oct	9.3	−2.1	223°	1.4	14.4
Nov	10.4	9.5	281°	2.5	24.0
Dec	9.1	−4.2	278°	1.7	18.8
Annual	9.5		250°	0.8	8.4

Table 11. Monthly and annual wind parameters at Redwood Falls.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	11.9	9.2	298°	5.1	45.6
Feb	11.4	4.6	296°	3.8	31.3
Mar	11.9	9.2	305°	2.9	23.1
Apr	12.6	15.6	42°	0.2	1.1
May	11.7	7.3	281°	0.7	5.8
Jun	10.5	−3.7	203°	2.2	20.0
Jul	9.2	−9.2	209°	2.1	21.4
Aug	9.3	−14.6	186°	2.9	30.1
Sep	9.8	−10.1	199°	2.2	0.7
Oct	11.2	2.8	249°	3.4	27.5
Nov	10.7	−1.8	287°	2.7	25.0
Dec	11.1	1.8	282°	2.3	19.9
Annual	10.9		261°	1.8	16.1

Table 12. Monthly and annual wind parameters at Rochester.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	14.7	13.9	266°	4.1	30.1
Feb	14.0	8.5	284°	3.8	26.6
Mar	13.7	6.2	304°	2.5	18.3
Apr	14.7	13.9	148°	0.9	6.6
May	13.2	2.3	213°	1.7	12.9
Jun	12.3	−4.7	199°	3.5	28.8
Jul	10.8	−16.3	223°	2.9	27.0
Aug	10.8	−16.3	213°	3.7	35.3
Sep	11.5	10.9	202°	2.6	23.1
Oct	13.1	1.5	234°	3.9	30.3
Nov	13.1	1.5	271°	3.5	26.9
Dec	13.3	3.1	265°	2.6	18.8
Annual	12.9		239°	2.4	19.3

Table 13. Monthly and annual wind parameters at Sioux Falls.

Month	Mean wind speed	Departure from annual mean	Resultant direction	Vector wind speed	Constancy of wind
	mi/hr	*percent*		*mi/hr*	*percent*
Jan	9.7	−2.0	317°	2.1	21.8
Feb	10.6	7.1	345°	1.8	16.7
Mar	11.7	8.1	352°	3.1	26.4
Apr	12.3	24.2	354°	2.6	21.4
May	10.4	5.1	10°	1.1	10.3
Jun	9.5	−4.0	154°	1.4	14.6
Jul	8.1	−18.2	160°	2.3	27.5
Aug	8.0	−19.2	152°	2.8	33.4
Sep	8.9	−10.1	225°	1.0	10.5
Oct	9.4	−5.1	249°	0.9	9.7
Nov	10.4	5.1	300°	3.3	31.6
Dec	9.5	−4.0	313°	2.6	28.2
Annual	9.9		323°	0.7	7.2

A generalized picture of the frequency of winds 3 mi/hr or less during the course of an average day is shown in Figure 17. While Figure 17 is based upon the Minneapolis-St. Paul station data, it is intended to represent any of the eight stations, not just Minneapolis-St. Paul. The data show that very light winds and calm periods are a summer and nighttime feature. Figure 17 also emphasizes the irregularity of winds as an energy source; this point would become even more apparent if individual days were considered.

This irregularity in wind speeds is an important feature of most meteorological elements. Though it is not possible to analyze this variability here in detail, the "Departure from Annual Mean" column in Tables 6-13 illustrates it to some degree. The absolute difference between the highest and lowest mean monthly speeds at each station ranges from a low of 2.9 mi/hr at Hibbing and International Falls to a high of 5.1 mi/hr at Duluth. In percentages, the differences range from 30.2% at International Falls to 46.4% at Duluth.

An example of the interannual variability possible in wind speed is shown in Table 14 at the Minneapolis-St. Paul station. In the normally high wind speed month of April there was nearly a 42% range between the successive years 1964 and 1965. In the low wind speed month of July the range in variability was nearly 35%, though not between successive years. On an annual basis the mean winds varied from 12.4% above the decade mean to 9.5% below it for a 21.9% interannual decade range. Thus, there are not only recognized and expected "windy" periods of hours and even several days, but also "windy" months and years.

Except under very unusual circumstances, structures are not designed to withstand the maximum possible wind. Rather, a structure is designed for the expected maximum wind it will be exposed to during its lifetime of, for example, 50 to 100 years. A compromise is therefore frequently made between absolute safety and pure economics. The purpose of the structure and its projected life largely determine the terms of the compromise, i.e., the return period of high wind that is selected. For a structure designed to withstand the maximum wind in 100 years—a reasonable safety factor —a 100-year record would theoretically be required. Such lengthy records are not yet available in Minnesota. However, the statistics of extreme values permit calculations to be made that in effect project a record, thus allowing an estimate to be made from a record considerably shorter than 100 years.

The "fastest mile", no longer measured at National Weather Service stations, was recorded by an anemometer that indicated the time interval for the passage of one mile of wind. The maximum fastest mile recorded in the study period at five stations, along with corresponding wind direction, is shown in Table 15. The single fastest mile of wind recorded during each year and the highest value from each year were combined to predict return periods of extreme winds for periods ranging from 2 to 500 years (Table 16). For 10- to 100-year return periods the highest winds are at Fargo. The lowest wind speeds are at Minneapolis-St. Paul for 2- to 10-year return periods and at Duluth for return periods greater than 10 years.

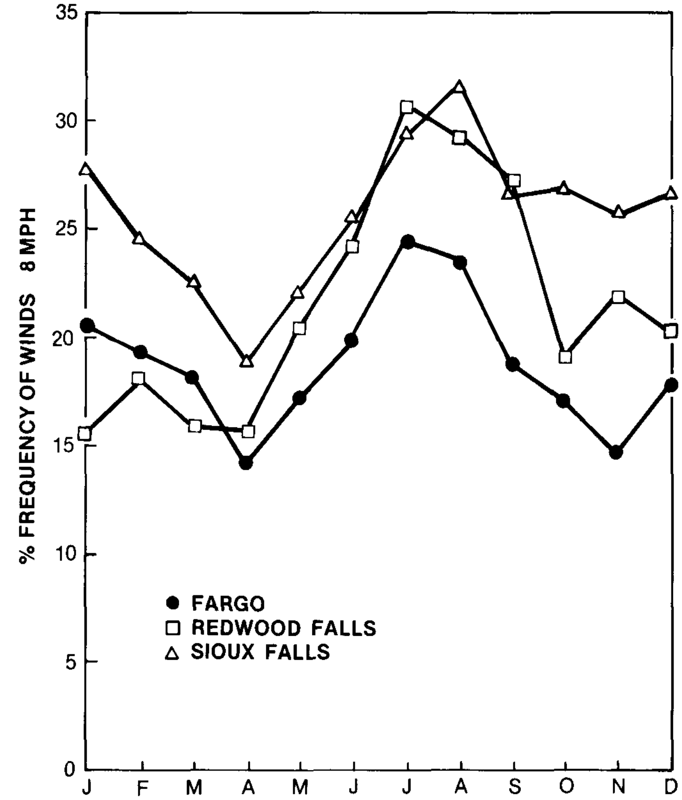

Figure 15. Mean monthly frequency of winds less than 8 mi/hr at Fargo, Redwood Falls, and Sioux Falls.

Wind directions associated with the fastest miles are shown in Table 17. At four stations fastest mile winds are from the northwest; at Duluth the direction of greatest frequency is the northeast. Interestingly, high north winds, while fairly frequent at the other stations, are absent at Duluth. The greatest distribution in wind direction is found at Minneapolis-St. Paul.

Thomann (20) has presented an interesting discussion on the effects of extreme winds on structures. Of particular interest is the wake or downwind effect which, when combined with wind force on the upwind side of an object, can explain certain structural failures.

Table 14. Variation of the April, July, and annual mean winds at Minneapolis-St. Paul over a 10-year period.

	April		July		Annual	
	Mean = 10.3 mi/hr		*Mean = 8.9 mi/hr*		*Mean = 10.5 mi/hr*	
Year	mi/hr	% from mean	mi/hr	% from mean	mi/hr	% from mean
1956	1.1	10.7	0.9	-10.1	1.1	10.5
1957	0.4	3.9	1.7	19.1	1.3	12.4
1958	1.2	11.7	0.8	9.0	0.8	7.6
1959	-0.3	-2.9	1.3	14.6	0.3	2.9
1960	0.1	1.0	-0.9	-10.1	-0.6	-5.7
1961	-1.6	-15.5	-1.2	-13.5	-1.0	-9.5
1962	0.1	1.0	-0.4	-4.5	0.3	2.9
1963	-1.2	-11.7	0.2	2.2	-0.8	-7.6
1964	2.1	20.4	-0.9	-10.1	0.0	0.0
1965	-2.2	-21.4	-1.4	-15.7	-0.9	-8.6

Table 15. Fastest mile recorded at five National Weather Service stations.[1]

Station	Period	Anemometer height in ft.	Date	Wind direction	Fastest mile[2] mi/hr
Duluth	1950-77	53	4/5/58	NE	70
Fargo	1942-77	86	6/9/59	NW	100
Huron	1939-77	41	7/3/57	NW	74
Mpls.- St. Paul	1938-77	75	7/20/51	W	82
Sioux City	1942-77	40	6/27/45	W	88

[1]Data are from Simiu et al. (15, 16).
[2]The fastest mile has been calculated for a uniform height of 10 m (32.8 ft) above the surface. The calculations are based upon wind speeds measured at the indicated anemometer heights.

Table 16. Predicted extreme wind in mi/hr for indicated periods.[1]

Return period	Duluth	Fargo	Huron	Minneapolis-St. Paul	Sioux City
	Station				
2	50	58	60	48	56
5	57	68	68	54	65
10	62	74	72	61	70
20	66	81	77	68	76
50	72	89	83	80	83
100	77	95	88	91	88
500	87	110	98	124	100

[1]Data are from Simiu, et al. (15, 16).

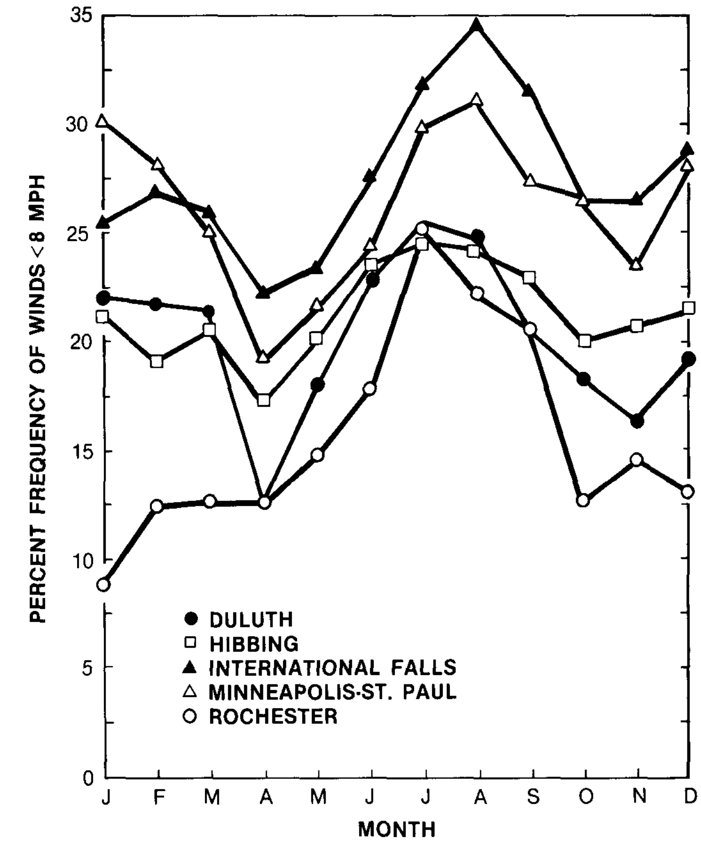

Figure 16. Mean monthly frequency of winds less than 8 mi/hr at Duluth, Hibbing, International Falls, Minneapolis-St. Paul, and Rochester.

Table 17. Frequency of wind directions associated with the fastest mile at five National Weather Service stations.[1]

Station	Number of observations	N	NE	E	SE	S	SW	W	NW
		Frequency of occurrence, in percent							
Duluth	28	0	39*	14	0	4	7	25	11
Fargo	36	25	0	0	8	6	8	22	31*
Huron	39	8	3	0	15	5	10	3	56*
Minneapolis-St. Paul	40	10	5	2	5	10	20	15	33*
Sioux City	36	11	0	0	0	14	14	17	44*

[1]Calculated from data by Simui et al. (15, 16).
*Maximum frequency of occurrence.

4. Resultant Wind, Vector Wind, and Wind Constancy

Resultant wind, vector wind and wind constancy are three parameters demonstrating important characteristics often overlooked. The resultant wind and vector wind combine wind speed and direction. Thus, they correct a deficiency of wind roses, which, as noted earlier, often represent only directional frequency and not speed.

Calculation of the vector and resultant winds, parameters also discussed by Brooks and Carruthers (1), follows Conrad's procedure (3). The objective is to determine the east-west and north-south components of the wind. For example, a northwest wind of 14.1 mi/hr can be thought of as a combination of a north wind of 10 mi/hr and a west wind of 10 mi/hr. Each component wind thus forms one leg of a right triangle with length proportional to its speed. The hypotenuse represents the resultant wind. In like manner, a southwest wind is composed of two parts, one a west and the other a south wind. A north or south wind has no east or west component and, conversely, an east or west wind has no north or south components. The two computed component vectors then yield the "resultant direction" [expressed in degrees] of the wind. The "vector wind

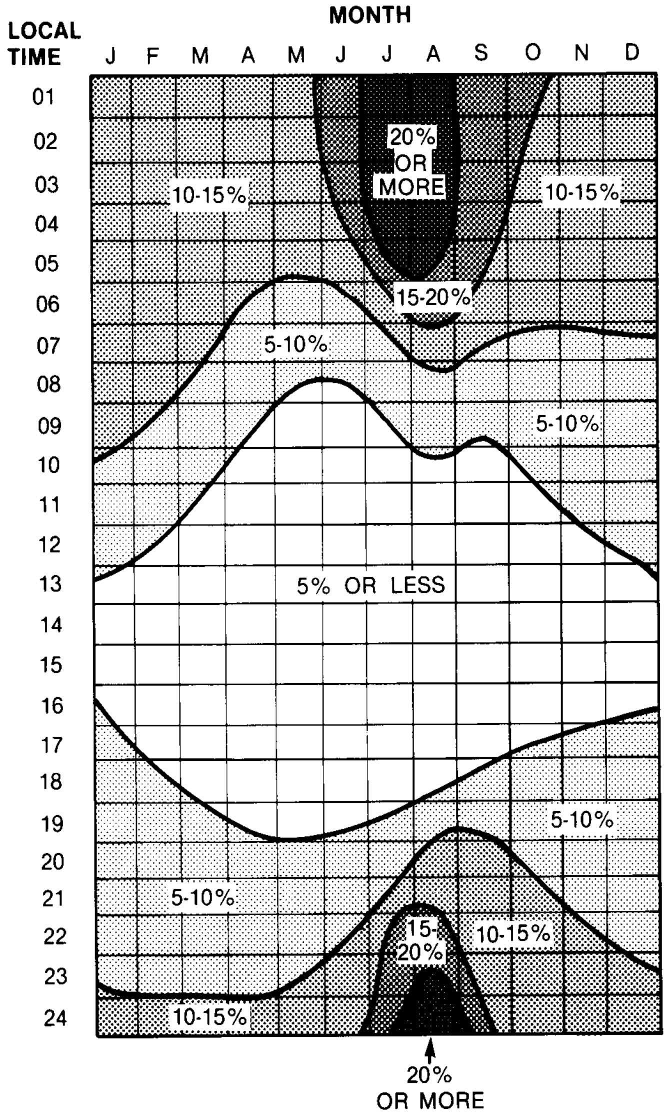

Figure 17. Mean hourly frequency in percent of winds 3 mi/hr or less during each month at Minneapolis-St. Paul.

speed" is the length of the wind vector whose orientation is the "resultant direction." Results of these calculations are shown in Tables 6-13.

The vector wind speed is the overall speed of the air when both speed and direction over a given period have been taken into account. A monthly vector represents the speed of a hypothetical air parcel that has been subjected to the different air motions during the month. For example, in the average January at Duluth a hypothetical parcel of air shows an overall movement from 295° (the resultant direction) and a speed of 4.2 mi/hr (the vector wind speed) in Table 6 and Figure 18, respectively. The vector wind speed is not to be confused with the mean wind speed, which for Duluth in January is 10.3 mi/hr.

The constancy of wind ranges from 0 to 100 with 0 representing wind vectors of equal value from all directions, and 100 representing winds from one direction only. Wind constancy is not comparable to the wind rose, since constancy includes wind speed in addition to direction.

Unlike the other stations, the Duluth station has a year-long high frequency of easterly winds—NE through SE—and they are the prevailing winds in May, June, and August (Table 4). The other stations have a higher frequency of southerly winds (Figures 7-14). Clearly, Lake Superior and the local topography strongly influence the Duluth data. The station's location, to the west of the crest of North Shore ridge and near the huge Lake Superior, is an anomaly among the other stations. Although the effect of the lake on the wind patterns is evident and significant, the extent to which the peculiarities of the site bias the data are not known. Consequently, the Duluth data should not be used to represent any other location. The vector winds, Figure 18, override the presence of the easterlies at Duluth, making them consistent for the most part with those at the other stations. The vector winds indicate a dominant northwesterly flow in the winter and a southerly flow in the summer.

The Duluth results demonstrate both the value and the difference between the wind rose and wind vector analyses. Each is a unique measurement tool.

B. Wind Power and Wind Energy

1. General Considerations

Careful planning should precede the construction of new wind power systems. Buick et al. (2) list three things that must be considered before establishing a wind power system. The first is the total amount of power available at a given site, which is a meteorological matter determined by site wind speed. The second item, more important than the first [according to Buick et al. (2)], is the total amount of energy (defined as the product of power and time) obtainable from a given wind system. The total energy (potential) is a function of the distribution and duration of particular wind speeds as well as of specific wind system characteristics. This is both a meteorological and an engineering matter. The third item is the structural strength necessary for the power system to withstand the imposed wind force. This is essentially an engineering problem solved with climatological data, particularly information regarding wind extremes.

An analysis of the limitations to the energy that can be extracted from the wind is given by Gustavson (9). He notes that the full potential of wind energy can never be realized. In addition to the part played by wind speed and its lack of constancy he describes other limiting factors. For example, it is not economical to build a machine capable of extracting the full energy from the maximum wind speed likely at a site. Thus, the full potential of a site can never be realized. To keep this loss of the potential wind energy to no more than about 15%, it is calculated that the maximum usable wind speed of a wind machine should be double the mean wind speed of the site.

There is also a practical limit to the amount of power that can be extracted from the wind. This was found to be 59.3% of the potential or meteorological power (7,8), a limitation known as the Betz coefficient in honor of

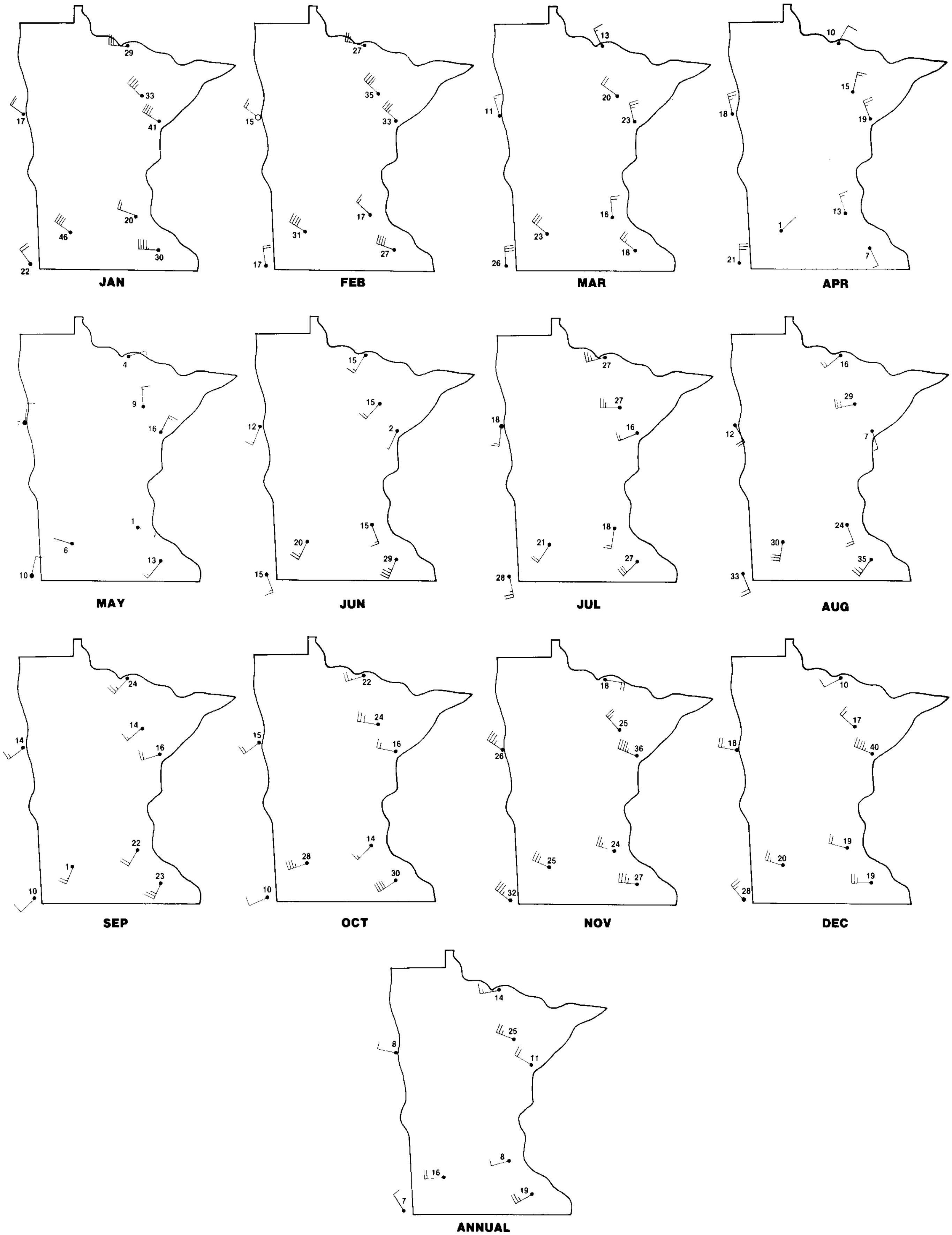

Figure 18. Vector wind speed (1 full barb is 1 mi/hr), resultant wind direction (wind arrow points in direction of wind), and constancy of wind (in percent at side of station location). Example: at Duluth in January the vector wind speed is 4.2 mi/hr (four and a fraction barbs), resultant wind direction is 298° (wind is blowing from 298°, approximately from WNW), and the constancy is 41 (41 adjacent to station circle).

the man who determined it. The limitation occurs because the "energy depleted wind must be transported from the site" (8). In other words, wind with all energy removed would have zero speed at the downwind side of the wind machine and some means of removing the air would have to be developed.

Another limitation to the extraction of energy is the number of wind machines that can be placed at a site, since energy consumption by each machine limits the number a given location can support. Studies cited by Gustavson (9) indicate that the machines should be separated by at least 5 to 15 times the rotor diameter.

2. Wind Energy Calculation

Kinetic energy is defined as $\frac{1}{2}mv^2$, where m is the mass and v the speed of an object. The mass, m, equals the product of the volume, V, and density, ρ. Kinetic energy then can be written as $\frac{1}{2}\rho V v^2$. For air moving past a wind system the volume of air equals the product of the area, A, swept by the blades and the speed, v, of the air. Thus the equation for the kinetic energy of air is $\frac{1}{2}\rho A v^3$ (4).

The power calculated with the formula $\frac{1}{2}\rho A v^3$, sometimes called meteorological power, is often used to compare sites (18) as is done in this bulletin. However, the calculated power, $\frac{1}{2}\rho A v^3$, is not the actual amount of power usable at a site for two important reasons. First, due to the Betz coefficient, only 59.3% of the calculated power value can be extracted and, second, the efficiency with which a wind machine extracts energy is further reduced due to such factors as DC-AC conversion, bearing friction, and blade feathering (17).

The potential (meteorological) wind power per unit area (P/A) with an air density of 1.225 kilograms per cubic meter (kg/m^3) is, in terms of Watts per square meter (Watts/m^2) (14):

P/A = 0.6125v^3 Watts/m^2, if v is expressed in meters per second (m/s)
= 0.05472v^3 Watts/m^2, if v is expressed in miles per hour (mi/hr)
= 0.08355v^3 Watts/m^2, if v is expressed in knots (kts).

The total power is obtained by finding the product of P/A for each wind speed class and the percentage of time of each wind speed class and then summing these products over all classes.

Watts per square meter (Watts/m^2) can be converted to kilowatt hours per day per square meter, kWatt hr/(day m^2), by multiplying by 0.024 (4). Conversion factors for the expression of Watts/m^2 into other units are (10):

$$
\begin{aligned}
1\ \text{Watt/m}^2 &= 14.34 \times 10^{-4}\ \text{cal/(cm}^2\ \text{min)} \\
&= 2.064\ \text{cal/(cm}^2\ \text{day)} \\
&= 52.83 \times 10^{-4}\ \text{BTU/(ft}^2\ \text{min)} \\
&= 7.608\ \text{BTU/(ft}^2\ \text{day)}
\end{aligned}
$$

Figure 19 shows the general relationship between meteorological power and the mean annual frequency distribution for wind speed classes at all eight stations. Essentially, there is an inverse relationship between the power associated with a given wind speed and the frequency of occurrence of that speed; maximum power is contained within winds that occur infrequently. This emphasizes the necessity for any wind power system to have a reservoir of energy or a backup energy system.

It is important to note that wind power varies with the cube of the wind speed. Thus, power increases rapidly with only a modest increase in speed; for example, a doubling of the speed increases the power eight times. A less obvious feature is that the distribution of wind speeds is required for the power equation. This is because the average power is not directly related to the average wind speed. That is, the cube of the average speed is not the same as the average value of the cube of the wind speeds. Two examples illustrate this. In the 8-12 mi/hr wind speed class the central value and average speed is 10 mi/hr, the cube of which is 1000. But since power is related to the cube of the speed, the average power for this class is obtained by cubing each speed from 8 through 12 mi/hr, for an average of 1060. This difference can be more dramatically illustrated with data from the Minneapolis-St. Paul station. Table 38 shows that the average July total wind power at Minneapolis-St. Paul is 75.7 Watts/m^2 when the distribution of wind speeds is considered. If, however, the mean July wind speed of 8.4 mi/hr (Table 10) had been used in the calculation, the indicated total wind power would be only 32.4 Watts/m^2.

Despite the foregoing example, Duncan (4) maintains that the use of the central value of each wind speed class may be justified because the distribution of winds is biased toward the lower values. Thus, the error resulting from use of the central value or mean of a wind class may be cancelled out.

3. Wind Power and Wind Energy in Minnesota

The wind power calculations in the following section were made using the formula P/A = 0.05472v^3 Watts/m^2 with v in mi/hr. The resulting figures represent the total meteorological power in Watts per square meter (Watts/m^2). A constant air density of 1.225 kg/m^3 was assumed throughout the year; the error created by using a constant density rather than allowing it to vary with the monthly temperature is very small. Reed, et al. (14) say the probability of error due to using a constant density it is no greater and may be smaller than possible error in the wind speed data. The v^3 values used are the means of the cubed wind speeds within each speed class rather than the cubes of the mean wind of each speed class.

Tables 18-25 show the frequency of occurrence of the wind speed classes at the eight stations. (These are the same speed classes devised by Sir Francis Beaufort in 1805.) Except at Redwood Falls and Rochester, where the highest frequency class generally is 13-18 mi/hr, the highest frequency occurs almost without fail in the 8-12 mi/hr class.

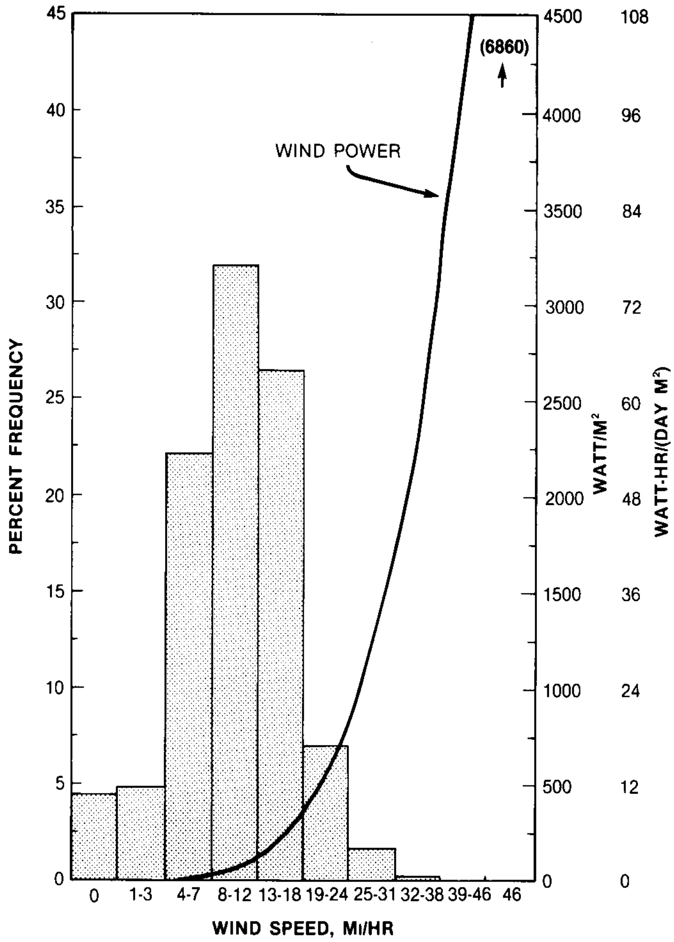

Figure 19. Mean annual occurrence of wind speed classes at all eight Minnesota stations and the meteorological power associated with each class.

The cumulative frequencies of wind speeds equal to or greater than the indicated speed are shown in Tables 26-33. Thus, depending upon the "cut-in" or minimum operating speed of the wind system, the operating time available at each station can be readily estimated. For example, in April at Duluth winds of at least 13 and 8 mi/hr, can be expected 47.8 and 82.3% of the time, respectively. In July the occurrence of these speeds at Duluth decreases to 27.8 and 66.2% of the time, respectively. Annually, the maximum frequency of winds at least 8 mi/hr ranges from 81.6% at Rochester to a minimum of 52.5% at International Falls. April is the month with the highest frequency of winds of at least 8 mi/hr at six stations. January is the maximum month at Redwood Falls and Rochester. As expected, the lowest frequencies at the eight stations are in July and August.

The "cut-out", "feathering," or maximum operable speed of many wind power systems is usually about 60 mi/hr, a speed occurring too infrequently to be included in Tables 18-25. As a result, data in Tables 26-33 represent the full potential for any "cut-in" speed matching the speeds shown.

Cumulative frequencies of wind speed classes at Hibbing and Rochester in April and August, which generally represent both the location and monthly extremes in speeds, are shown in Figure 20. The other six stations and 10 months fall within the frequency ranges shown.

The average monthly frequencies listed in Tables 18-25 were converted to wind energy in kilowatt-hr/m^2 in each wind speed class for each station. The results are listed in Tables 35-41 along with the monthly total (meteorological) wind power for each of the eight stations. The cumulative power for what are often the two extreme months, April and August, at the two stations usually showing extreme values, Hibbing and Rochester, is illustrated in Figure 21. With a few exceptions, all other stations and months will fall between these extremes.

Table 18. Frequency of occurrence of wind speed classes at Duluth.

	Wind speed classes in miles per hour											
Month	0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46	Mean speed	Median speed
					percent						*mi/hr*	*mi/hr*
Jan	1.5	8.3	22.0	34.9	24.5	7.0	1.6	0.2	0.0	0.0	10.3	10.6
Feb	0.9	6.8	21.8	33.8	26.5	7.8	1.9	0.5	0.0	0.0	10.8	11.0
Mar	2.0	6.5	21.3	32.8	25.7	9.3	2.1	0.3	0.0	0.0	10.9	11.1
Apr	1.2	3.9	12.6	34.5	29.0	13.0	4.8	0.9	0.1	0.0	12.7	12.7
May	0.8	5.2	18.0	32.9	27.9	11.3	3.5	0.4	0.0	0.0	11.9	12.0
Jun	1.5	6.7	22.8	37.5	24.1	5.9	1.3	0.2	0.0	0.0	10.1	10.5
Jul	1.6	6.7	25.5	38.4	22.5	4.7	0.6	0.0	0.0	0.0	7.6	10.1
Aug	1.7	6.8	24.7	40.3	22.3	3.8	0.4	0.0	0.0	0.0	9.5	10.1
Sep	1.2	4.9	20.2	37.8	26.4	8.2	1.2	0.1	0.0	0.0	10.8	11.1
Oct	1.2	5.0	18.3	35.6	28.1	9.6	2.1	0.1	0.0	0.0	11.3	11.6
Nov	1.0	4.3	16.3	32.6	28.3	12.3	4.5	0.7	0.0	0.0	12.4	12.4
Dec	1.1	5.3	19.2	35.3	28.2	8.6	1.9	0.3	0.1	0.0	11.3	11.5
Annual	1.3	5.9	20.4	35.3	26.1	8.5	2.2	0.3	0.0	0.0	11.0	11.2

Table 19. Frequency of occurrence of wind speed classes at Fargo.

Month	Wind speed classes in miles per hour										Mean speed	Median speed
	0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46		
	percent										*mi/hr*	*mi/hr*
Jan	0.9	6.2	20.5	32.1	25.6	10.5	3.9	0.3	0.0	0.0	11.6	11.5
Feb	1.2	5.7	19.3	33.1	26.7	10.3	3.5	0.2	0.0	0.0	11.6	11.6
Mar	0.8	4.9	18.2	31.6	28.7	11.9	3.4	0.5	0.0	0.0	12.1	12.1
Apr	0.7	3.2	14.1	29.7	30.1	14.8	6.3	1.1	0.0	0.0	13.6	13.5
May	0.7	4.3	17.2	32.0	29.0	11.9	4.3	0.6	0.0	0.0	12.4	12.3
Jun	0.9	5.6	19.8	33.9	27.5	9.7	2.3	0.3	0.0	0.0	11.4	11.5
Jul	1.4	7.1	24.4	36.9	23.7	5.4	0.9	0.2	0.0	0.0	9.9	10.3
Aug	1.3	6.0	23.5	36.8	24.3	6.7	1.4	0.0	0.0	0.0	10.4	10.6
Sep	0.6	4.9	18.7	33.5	28.9	10.4	2.8	0.2	0.0	0.0	11.7	11.9
Oct	0.5	4.0	17.0	32.2	29.6	11.9	4.4	0.4	0.0	0.0	12.5	12.4
Nov	0.5	3.4	14.7	30.0	29.1	14.2	6.6	1.5	0.0	0.0	13.6	13.3
Dec	0.9	5.9	17.9	31.6	28.1	10.3	4.2	0.6	0.0	0.0	12.1	12.0
Annual	0.8	5.1	18.8	32.8	27.6	10.7	3.7	0.5	0.0	0.0	11.9	11.9

Table 20. Frequency of occurrence of wind speed classes at Hibbing.

Month	Wind speed classes in miles per hour										Mean speed	Median speed
	0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46		
	percent										*mi/hr*	*mi/hr*
Jan	13.5	3.5	21.3	31.2	27.5	2.7	0.2	0.0	0.0	0.0	9.3	9.9
Feb	15.9	2.8	19.1	31.6	27.2	2.9	0.5	0.0	0.0	0.0	9.2	9.9
Mar	13.5	2.8	20.5	31.3	28.3	3.2	0.5	0.0	0.0	0.0	9.5	10.1
Apr	10.8	2.5	17.3	30.7	32.4	5.7	0.6	0.0	0.0	0.0	10.6	11.2
May	10.8	2.7	20.2	19.1	41.8	4.6	0.8	0.0	0.0	0.0	10.8	12.3
Jun	15.0	2.5	23.6	31.8	24.0	2.9	0.2	0.0	0.0	0.0	9.0	9.4
Jul	17.8	3.2	24.6	31.4	21.0	2.0	0.1	0.0	0.0	0.0	8.3	8,7
Aug	21.0	3.2	24.2	29.4	19.8	2.3	0.1	0.0	0.0	0.0	7.9	8.3
Sep	17.8	2.8	22.9	30.7	23.5	2.1	0.1	0.0	0.0	0.0	8.6	9.0
Oct	12.2	2.8	20.1	30.9	28.3	5.0	0.6	0.1	0.0	0.0	9.9	10.4
Nov	13.6	2.9	20.8	31.9	27.6	2.9	0.4	0.0	0.0	0.0	9.5	10.0
Dec	14.6	3.2	21.5	35.0	22.5	3.0	0.2	0.0	0.0	0.0	8.9	9.6
Annual	14.7	2.9	21.3	30.4	27.0	3.3	0.4	0.0	0.0	0.0	9.3	9.8

Table 21. Frequency of occurrence of wind speed classes at International Falls.

Month	Wind speed classes in miles per hour										Mean speed	Median speed
	0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46		
	percent										*mi/hr*	*mi/hr*
Jan	7.1	2.8	25.4	37.2	22.4	4.6	0.5	0.0	0.0	0.0	9.8	10.0
Feb	6.8	2.6	26.9	36.6	21.8	4.5	0.8	0.0	0.0	0.0	9.8	9.9
Mar	7.5	1.6	25.8	36.2	24.0	4.2	0.8	0.0	0.0	0.0	9.9	10.1
Apr	4.3	1.5	22.2	37.1	26.4	7.4	0.9	0.1	0.0	0.0	11.1	11.0
May	5.8	1.5	23.3	35.5	26.3	6.0	1.5	0.0	0.0	0.0	10.6	10.7
Jun	8.3	3.2	27.6	36.0	20.8	3.6	0.5	0.0	0.0	0.0	9.4	9.5
Jul	9.3	3.4	31.8	35.6	16.8	2.8	0.2	0.1	0.0	0.0	8.7	8.8
Aug	11.9	3.7	34.5	31.8	15.9	2.0	0.4	0.0	0.0	0.0	8.2	8.0
Sep	8.0	2.6	31.5	34.2	19.6	3.8	0.3	0.0	0.0	0.0	9.2	9.2
Oct	5.5	2.5	26.5	38.3	22.3	4.4	0.6	0.0	0.0	0.0	9.9	10.0
Nov	6.5	2.4	26.4	38.0	23.4	3.2	0.1	0.0	0.0	0.0	9.8	9.9
Dec	7.3	3.0	28.8	39.0	18.7	3.1	0.2	0.0	0.0	0.0	9.2	9.4
Annual	7.4	2.6	27.6	36.3	21.5	4.1	0.6	0.0	0.0	0.0	9.6	8.3

Table 22. Frequency of occurrence of wind speed classes at Minneapolis-St. Paul.

Month	0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46	Mean speed	Median speed
					percent						*mi/hr*	*mi/hr*
Jan	0.8	10.0	30.2	32.3	22.6	3.7	0.4	0.0	0.0	0.0	8.9	9.6
Feb	1.0	9.9	28.2	34.0	21.5	4.5	0.9	0.0	0.0	0.0	9.3	9.6
Mar	1.2	7.8	25.0	34.6	24.2	6.2	1.0	0.0	0.0	0.0	9.9	10.3
Apr	0.9	7.3	19.3	31.2	29.3	9.8	2.1	0.1	0.0	0.0	11.2	11.6
May	1.0	7.3	21.7	33.6	27.5	7.5	1.3	0.1	0.0	0.0	10.6	11.0
Jun	1.3	7.7	24.4	37.3	24.2	4.6	0.5	0.0	0.0	0.0	9.7	10.2
Jul	2.4	10.7	29.8	36.7	18.2	2.1	0.1	0.0	0.0	0.0	8.4	9.0
Aug	2.0	12.8	31.1	36.4	15.9	1.8	0.0	0.0	0.0	0.0	8.1	8.6
Sep	1.5	9.6	27.3	35.3	21.6	4.1	0.6	0.0	0.0	0.0	9.3	9.6
Oct	1.9	9.0	26.5	35.0	21.8	5.0	0.8	0.0	0.0	0.0	9.3	9.8
Nov	1.0	7.2	23.5	33.6	25.7	7.5	1.5	0.0	0.0	0.0	10.4	10.7
Dec	1.4	9.1	28.1	35.8	21.4	3.6	0.6	0.0	0.0	0.0	9.1	9.6
Annual	1.4	9.0	26.2	35.0	22.5	5.0	0.9	0.0	0.0	0.0	9.5	9.9

Wind speed classes in miles per hour

Table 23. Frequency of occurrence of wind speed classes at Redwood Falls.

Month	0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46	Mean speed	Median speed
					percent						*mi/hr*	*mi/hr*
Jan	3.3	1.1	15.5	35.1	37.3	6.3	1.2	0.2	0.0	0.0	11.9	12.3
Feb	4.4	1.5	18.0	33.6	36.0	5.0	1.1	0.2	0.0	0.0	11.4	11.9
Mar	4.2	1.4	15.9	33.1	37.5	5.8	1.9	0.2	0.0	0.0	11.9	12.3
Apr	2.8	1.3	15.6	28.0	41.3	8.6	1.9	0.3	0.1	0.0	12.6	13.0
May	3.8	1.6	20.3	30.8	35.7	5.7	1.8	0.2	0.2	0.0	11.7	12.0
Jun	5.4	2.2	24.1	33.2	30.3	3.9	0.8	0.1	0.0	0.0	10.5	10.8
Jul	6.9	2.2	30.7	35.3	23.0	1.8	0.1	0.0	0.0	0.0	9.2	9.4
Aug	6.1	2.9	29.1	37.2	23.2	1.4	0.1	0.0	0.0	0.0	9.3	9.6
Sep	5.8	3.2	27.2	33.9	26.8	2.7	0.5	0.0	0.0	0.0	9.8	10.1
Oct	3.9	1.9	19.2	34.4	35.1	4.7	0.8	0.0	0.0	0.0	11.2	11.6
Nov	4.2	1.9	21.9	38.1	29.1	3.9	1.0	0.0	0.0	0.0	10.7	10.9
Dec	4.0	1.5	20.2	35.8	33.2	4.4	0.9	0.0	0.0	0.0	11.1	11.4
Annual	4.6	1.9	21.5	34.0	32.4	4.5	1.0	0.1	0.0	0.0	10.9	11.2

Wind speed classes in miles per hour

Table 24. Frequency of occurrence of wind speed classes at Rochester.

Month	0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46	Mean speed	Median speed
					percent						*mi/hr*	*mi/hr*
Jan	1.0	1.0	8.9	27.3	37.4	18.4	5.0	0.9	0.0	0.0	14.7	14.9
Feb	1.0	1.2	12.4	29.4	34.2	16.5	4.3	0.8	0.1	0.0	14.0	14.0
Mar	1.2	1.1	12.6	30.6	35.2	14.1	4.3	0.8	0.0	0.0	13.7	13.9
Apr	1.5	0.6	12.0	25.3	35.7	18.6	5.2	0.8	0.2	0.0	14.7	14.8
May	1.6	1.3	14.8	30.8	34.2	13.5	3.4	0.2	0.1	0.0	13.2	13.3
Jun	1.7	1.5	17.8	34.2	33.6	9.5	1.6	0.1	0.0	0.0	12.3	12.2
Jul	1.5	1.9	25.2	37.9	27.8	5.2	0.5	0.0	0.0	0.0	10.8	10.8
Aug	1.5	1.9	22.2	42.2	27.2	4.8	0.2	0.0	0.0	0.0	10.8	10.9
Sep	1.9	1.9	20.5	38.7	28.8	7.5	0.8	0.0	0.0	0.0	11.5	11.8
Oct	1.0	0.8	12.6	34.1	36.9	11.7	2.6	0.2	0.0	0.0	13.1	13.2
Nov	1.0	1.5	14.0	33.1	35.8	12.0	2.2	0.4	0.0	0.0	13.1	13.1
Dec	1.7	1.5	13.1	30.4	35.6	14.9	2.7	0.2	0.0	0.0	13.3	13.6
Annual	1.4	1.4	15.5	32.8	33.5	12.2	2.7	0.4	0.0	0.0	12.9	12.8

Wind speed classes in miles per hour

Table 25. Frequency of occurrence of wind speed classes at Sioux Falls.

Month	Wind speed classes in miles per hour: 0	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	>46	Mean speed	Median speed
	percent										*mi/hr*	*mi/hr*
Jan	2.0	9.6	27.9	28.7	21.7	7.5	2.2	0.4	0.0	0.0	9.7	9.8
Feb	2.0	8.2	24.5	28.3	25.1	9.7	2.2	0.0	0.0	0.0	10.6	10.7
Mar	3.0	7.0	22.5	26.7	23.7	12.3	4.4	0.4	0.0	0.0	11.7	11.3
Apr	2.0	5.6	18.9	28.3	28.1	12.2	4.5	0.4	0.0	0.0	12.3	12.2
May	5.0	8.9	22.0	29.4	24.6	7.5	2.2	0.4	0.0	0.0	10.4	10.4
Jun	3.0	10.2	25.4	31.9	22.0	6.4	1.1	0.0	0.0	0.0	9.5	9.8
Jul	4.0	13.6	29.3	32.8	17.9	2.4	0.0	0.0	0.0	0.0	8.1	8.5
Aug	5.0	12.9	31.7	30.9	17.1	2.4	0.0	0.0	0.0	0.0	8.0	8.1
Sep	6.0	11.4	26.6	29.2	20.9	5.4	0.5	0.0	0.0	0.0	8.9	9.0
Oct	4.0	10.4	26.8	30.0	21.3	6.4	1.1	0.0	0.0	0.0	9.4	9.5
Nov	2.0	9.3	25.7	29.2	21.7	7.9	3.4	0.8	0.0	0.0	10.4	10.2
Dec	4.0	10.4	26.6	29.0	20.9	7.5	1.6	0.0	0.0	0.0	9.5	9.6
Annual	3.5	9.8	25.6	29.5	22.1	7.3	1.9	0.3	0.0	0.0	9.9	9.9

Table 26. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at Duluth.

Month	Miles per hour: 46	39	32	25	19	13	8	4	1	0
	percent									
Jan	0.0	0.0	0.2	1.8	8.8	33.3	68.2	90.2	98.5	100.0
Feb	0.0	0.0	0.5	2.4	10.2	36.7	70.5	92.3	99.1	100.0
Mar	0.0	0.0	0.3	2.4	11.7	37.4	70.2	91.5	98.0	100.0
Apr	0.0	0.1	1.0	5.8	18.8	47.8	82.3	94.9	98.9	100.0
May	0.0	0.0	0.4	3.9	15.2	43.1	76.0	94.0	99.2	100.0
Jun	0.0	0.0	0.2	1.5	7.4	31.5	69.0	91.8	98.5	100.0
Jul	0.0	0.0	0.0	0.6	5.3	27.8	66.2	91.7	98.4	100.0
Aug	0.0	0.0	0.0	0.4	4.2	26.5	66.8	91.5	98.3	100.0
Sep	0.0	0.0	0.1	1.3	9.5	35.9	73.7	93.9	98.8	100.0
Oct	0.0	0.0	0.1	2.2	11.8	39.9	75.5	93.8	98.8	100.0
Nov	0.0	0.0	0.7	5.2	17.5	45.8	78.4	94.7	99.0	100.0
Dec	0.0	0.1	0.4	2.3	10.9	39.1	74.4	93.6	98.9	100.0
Annual	0.0	0.0	0.3	2.5	11.0	37.1	72.4	92.8	98.7	100.0

Table 27. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at Fargo.

Month	Miles per hour: 46	39	32	25	19	13	8	4	1	0
	percent									
Jan	0.0	0.0	0.3	4.2	14.7	40.3	72.4	92.9	99.1	100.0
Feb	0.0	0.0	0.2	3.7	14.0	40.7	73.8	93.1	98.8	100.0
Mar	0.0	0.0	0.5	3.9	15.8	44.5	76.1	94.3	99.2	100.0
Apr	0.0	0.0	1.1	7.4	22.2	52.3	82.0	96.1	99.3	100.0
May	0.0	0.0	0.6	4.9	16.8	45.8	77.8	95.0	99.3	100.0
Jun	0.0	0.0	0.3	2.6	12.3	39.8	73.7	93.5	99.1	100.0
Jul	0.0	0.0	0.2	1.1	6.5	30.2	67.1	91.5	98.6	100.0
Aug	0.0	0.0	0.0	1.4	8.1	32.4	69.2	92.7	98.7	100.0
Sep	0.0	0.0	0.2	3.0	13.4	42.3	75.8	94.5	99.4	100.0
Oct	0.0	0.0	0.4	4.8	16.7	46.3	78.5	95.5	99.5	100.0
Nov	0.0	0.0	1.5	8.1	22.3	51.4	81.4	96.1	99.5	100.0
Dec	0.0	0.0	0.6	4.8	15.1	43.7	75.3	93.2	99.1	100.0
Annual	0.0	0.0	0.5	4.2	14.9	42.5	75.3	94.1	99.2	100.0

Table 28. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at Hibbing.

Month	46	39	32	25	19	13	8	4	1	0
					percent					
Jan	0.0	0.0	0.0	0.2	2.9	30.4	61.6	82.9	86.4	100.0
Feb	0.0	0.0	0.0	0.5	3.4	30.6	62.2	81.3	84.1	100.0
Mar	0.0	0.0	0.0	0.5	3.7	32.0	63.3	83.8	86.6	100.0
Apr	0.0	0.0	0.0	0.6	6.3	38.7	69.4	86.7	89.2	100.0
May	0.0	0.0	0.0	0.8	5.4	47.2	66.3	86.5	89.2	100.0
Jun	0.0	0.0	0.0	0.2	3.1	27.1	58.9	82.5	85.0	100.0
Jul	0.0	0.0	0.0	0.1	2.1	23.1	54.5	79.1	82.3	100.0
Aug	0.0	0.0	0.0	0.1	2.4	22.2	51.6	75.8	79.0	100.0
Sep	0.0	0.0	0.0	0.1	2.2	25.7	56.4	79.3	82.1	100.0
Oct	0.0	0.0	0.1	0.7	5.7	34.0	64.9	85.0	87.8	100.0
Nov	0.0	0.0	0.0	0.4	3.3	30.9	62.8	83.6	86.5	100.0
Dec	0.0	0.0	0.0	0.2	3.2	25.7	60.7	82.2	85.4	100.0
Annual	0.0	0.0	0.0	0.4	3.7	30.7	61.1	82.4	85.3	100.0

Miles per hour

Table 29. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at International Falls.

Month	46	39	32	25	19	13	8	4	1	0
					percent					
Jan	0.0	0.0	0.0	0.5	5.1	27.5	64.7	90.1	92.9	100.0
Feb	0.0	0.0	0.0	0.8	5.3	27.1	63.7	90.6	93.2	100.0
Mar	0.0	0.0	0.0	0.8	5.0	29.0	65.2	91.0	92.6	100.0
Apr	0.0	0.0	0.1	1.0	8.4	34.8	71.9	94.1	95.6	100.0
May	0.0	0.0	0.0	1.5	7.5	33.8	69.3	92.6	94.1	100.0
Jun	0.0	0.0	0.0	0.5	4.1	24.9	60.9	88.5	91.7	100.0
Jul	0.0	0.0	0.1	0.3	3.1	19.9	55.5	87.3	90.7	100.0
Aug	0.0	0.0	0.0	0.4	2.4	18.3	50.1	84.6	88.3	100.0
Sep	0.0	0.0	0.0	0.3	4.1	23.7	57.9	89.4	92.0	100.0
Oct	0.0	0.0	0.0	0.6	5.0	27.3	65.6	92.1	94.6	100.0
Nov	0.0	0.0	0.0	0.1	3.3	26.7	64.7	91.1	93.5	100.0
Dec	0.0	0.0	0.0	0.2	3.3	22.0	61.0	89.8	92.8	100.0
Annual	0.0	0.0	0.0	0.6	4.7	26.2	52.5	80.1	82.7	100.0

Miles per hour

Table 30. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at Minneapolis-St. Paul.

Month	46	39	32	25	19	13	8	4	1	0
					percent					
Jan	0.0	0.0	0.0	0.4	4.1	26.7	59.0	89.2	99.2	100.0
Feb	0.0	0.0	0.0	0.9	5.4	26.9	60.9	89.1	99.0	100.0
Mar	0.0	0.0	0.0	1.0	7.2	31.4	66.0	91.0	98.8	100.0
Apr	0.0	0.0	0.1	2.2	12.0	41.3	72.5	91.8	99.1	100.0
May	0.0	0.0	0.1	1.4	8.9	36.4	70.0	91.7	99.0	100.0
Jun	0.0	0.0	0.0	0.5	5.1	29.3	66.6	91.0	98.7	100.0
Jul	0.0	0.0	0.0	0.1	2.2	20.4	57.1	86.9	97.6	100.0
Aug	0.0	0.0	0.0	0.0	1.8	17.7	54.1	85.2	98.0	100.0
Sep	0.0	0.0	0.0	0.6	4.7	26.3	61.6	88.9	98.5	100.0
Oct	0.0	0.0	0.0	0.8	5.8	27.6	62.6	89.1	98.1	100.0
Nov	0.0	0.0	0.0	1.5	9.0	34.7	68.3	91.8	99.0	100.0
Dec	0.0	0.0	0.0	0.6	4.2	25.6	61.4	89.5	98.6	100.0
Annual	0.0	0.0	0.0	0.9	5.9	28.4	63.4	89.6	98.6	100.0

Miles per hour

Table 31. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at Redwood Falls.

Month	Miles per hour									
	46	39	32	25	19	13	8	4	1	0
	percent									
Jan	0.0	0.0	0.2	1.4	7.7	45.0	80.1	95.6	96.7	100.0
Feb	0.0	0.0	0.2	1.3	6.3	42.3	75.9	93.9	95.4	100.0
Mar	0.0	0.0	0.2	2.1	7.9	45.4	78.5	94.4	95.8	100.0
Apr	0.0	0.0	0.1	0.4	9.0	50.3	78.3	93.9	95.2	100.0
May	0.0	0.2	0.4	2.2	7.9	43.6	74.4	94.7	96.3	100.0
Jun	0.0	0.0	0.1	0.9	4.8	35.1	68.3	92.4	94.6	100.0
Jul	0.0	0.0	0.0	0.1	1.9	24.9	60.2	90.9	93.1	100.0
Aug	0.0	0.0	0.0	0.1	1.5	24.7	61.9	91.0	93.9	100.0
Sep	0.0	0.0	0.0	0.5	3.2	30.0	63.9	91.1	94.3	100.0
Oct	0.0	0.0	0.0	0.8	5.5	40.6	75.0	94.2	96.1	100.0
Nov	0.0	0.0	0.0	1.0	4.9	34.0	72.1	94.0	95.9	100.0
Dec	0.0	0.0	0.0	0.9	5.3	38.5	74.3	94.5	96.0	100.0
Annual	0.0	0.0	0.1	1.0	5.5	37.9	71.9	93.4	95.3	100.0

Table 32. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at Rochester.

Month	Miles per hour									
	46	39	32	25	19	13	8	4	1	0
	percent									
Jan	0.0	0.0	0.9	5.9	24.3	61.7	89.0	97.9	98.9	100.0
Feb	0.0	0.1	0.9	5.2	21.7	55.9	85.3	97.7	98.9	100.0
Mar	0.0	0.0	0.8	5.1	19.2	54.4	85.0	97.6	98.7	100.0
Apr	0.0	0.2	1.0	6.2	24.8	60.5	85.8	97.8	98.4	100.0
May	0.0	0.1	0.3	3.7	17.2	51.4	82.2	97.0	98.3	100.0
Jun	0.0	0.0	0.1	1.7	11.2	44.8	79.0	96.8	98.3	100.0
Jul	0.0	0.0	0.0	0.5	5.7	33.5	71.4	96.6	98.5	100.0
Aug	0.0	0.0	0.0	0.2	5.0	32.2	74.4	96.6	98.5	100.0
Sep	0.0	0.0	0.0	0.8	8.3	37.1	75.8	96.3	98.2	100.0
Oct	0.0	0.0	0.2	2.8	14.5	51.4	85.5	98.1	98.9	100.0
Nov	0.0	0.0	0.4	2.6	14.6	50.4	83.5	97.5	99.0	100.0
Dec	0.0	0.0	0.2	2.9	17.8	53.4	83.8	96.9	98.4	100.0
Annual	0.0	0.0	0.4	3.1	15.3	48.8	81.6	97.1	98.5	100.0

Table 33. Probability of occurrence of wind speeds equal to or greater than the indicated speeds at Sioux Falls.

Month	Miles per hour									
	46	39	32	25	19	13	8	4	1	0
	percent									
Jan	0.0	0.0	0.4	2.6	10.1	31.8	60.5	88.4	98.0	100.0
Feb	0.0	0.0	0.0	2.2	11.9	37.0	65.3	89.8	98.0	100.0
Mar	0.0	0.0	0.4	4.8	17.1	40.8	67.5	90.0	97.0	100.0
Apr	0.0	0.0	0.4	4.9	17.1	45.2	73.5	92.4	98.0	100.0
May	0.0	0.0	0.4	2.6	10.1	34.7	64.1	86.1	95.0	100.0
Jun	0.0	0.0	0.0	1.1	7.5	29.5	61.4	86.8	97.0	100.0
Jul	0.0	0.0	0.0	0.0	2.4	20.3	53.1	82.4	96.0	100.0
Aug	0.0	0.0	0.0	0.0	2.4	19.5	50.4	82.1	95.0	100.0
Sep	0.0	0.0	0.0	0.5	5.9	26.8	56.0	82.6	94.0	100.0
Oct	0.0	0.0	0.0	1.1	7.5	28.8	58.8	85.6	96.0	100.0
Nov	0.0	0.0	0.8	4.2	12.1	33.8	63.0	88.7	98.0	100.0
Dec	0.0	0.0	0.0	1.6	9.1	30.0	59.0	85.6	96.0	100.0
Annual	0.0	0.0	0.3	2.2	9.5	31.6	61.1	86.7	96.5	100.0

Table 34. Monthly and annual wind energy, kWatt hr/m² in each wind speed class, and the average monthly wind power, Watts/m², at Duluth.

Month	Wind speed class in miles per hour								Total	Average power Watts/m²
	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46		
				kWatt hr/m²						
Jan	0.04	1.68	15.06	38.50	28.87	14.51	3.55	—	102.21	137.3
Feb	0.03	1.50	13.17	37.61	29.04	15.61	8.05	—	105.01	156.2
Mar	0.03	1.62	14.15	40.38	38.35	19.03	5.21	—	118.77	159.8
Apr	0.02	0.93	14.41	44.10	51.87	42.20	15.40	2.97	171.90	238.7
May	0.03	1.37	14.20	43.84	46.60	31.71	7.11	—	144.86	194.7
Jun	0.03	1.68	15.66	36.64	23.55	11.46	3.32	—	92.34	128.3
Jul	0.03	1.94	16.57	35.35	19.39	5.49	—	—	78.77	105.8
Aug	0.03	1.88	17.39	35.04	15.68	3.66	—	—	73.68	99.0
Sep	0.02	1.49	15.79	40.15	32.69	10.49	1.66	—	102.29	142.2
Oct	0.02	1.39	15.36	44.16	39.56	19.03	1.66	—	121.18	163.1
Nov	0.02	1.20	13.61	43.04	49.48	39.52	11.85	—	158.72	220.0
Dec	0.03	1.46	15.23	44.31	35.46	17.20	5.21	2.97	121.87	164.2
Annual	0.33	18.14	180.61	483.12	410.55	229.89	63.02	5.93	1391.60	159.1

Table 35. Monthly and annual wind energy, kWatt hr/m² in each wind speed class, and the average monthly wind power, Watts/m², at Fargo.

Month	Wind speed class in miles per hour								Total	Average power Watts/m²
	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46		
				kWatt hr/m²						
Jan	0.03	1.56	13.85	40.23	43.28	35.37	5.21	—	139.53	187.7
Feb	0.03	1.33	12.90	37.89	38.34	28.66	3.08	—	122.23	182.1
Mar	0.02	1.39	13.64	45.09	49.04	30.86	8.77	—	148.81	200.1
Apr	0.02	1.04	12.40	45.76	59.07	55.37	18.72	—	192.38	267.1
May	0.02	1.31	13.81	45.57	49.04	39.03	10.66	—	159.44	214.2
Jun	0.03	1.46	14.16	41.82	38.68	20.24	5.21	—	121.60	168.7
Jul	0.03	1.86	15.92	37.23	22.28	8.17	3.55	—	89.04	119.6
Aug	0.03	1.79	15.88	38.18	27.60	12.68	—	—	96.16	129.3
Sep	0.02	1.38	13.99	43.95	41.50	24.64	3.32	—	128.80	178.9
Oct	0.02	1.29	13.90	46.50	49.04	39.88	7.11	—	157.74	212.0
Nov	0.02	1.08	12.53	44.24	56.63	57.93	25.59	—	198.02	275.1
Dec	0.03	1.36	13.64	44.94	42.45	38.05	10.66	—	151.13	202.0
Annual	0.30	16.85	166.62	511.40	516.95	390.88	101.88	—	1704.88	194.7

Table 36. Monthly and annual wind energy, kWatt hr/m² in each wind speed class, and the average monthly wind power, Watts/m², at Hibbing.

Month	Wind speed class in miles per hour								Total	Average power Watts/m²
	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46		
				kWatt hr/m²						
Jan	0.02	1.62	13.46	43.21	11.13	1.83	—	—	71.27	95.8
Feb	0.01	1.31	12.32	38.61	10.80	4.15	—	—	67.20	99.9
Mar	0.01	1.56	13.51	44.48	13.19	4.51	—	—	77.26	103.9
Apr	0.01	1.28	12.82	49.27	22.72	5.24	—	—	91.34	126.9
May	0.01	1.54	8.24	65.68	18.95	7.32	—	—	101.74	136.7
Jun	0.01	1.74	13.28	36.49	11.58	1.71	—	—	64.81	90.1
Jul	0.02	1.87	13.55	32.99	8.26	0.85	—	—	57.54	77.4
Aug	0.02	1.84	12.68	31.11	9.48	0.85	—	—	55.98	75.3
Sep	0.01	1.69	12.82	35.73	8.37	0.85	—	—	59.47	82.7
Oct	0.01	1.53	13.33	44.48	20.61	5.49	0.85	—	86.30	117.2
Nov	0.01	1.53	13.32	41.96	11.58	3.54	—	—	71.94	99.9
Dec	0.02	1.64	15.10	35.35	12.36	1.83	—	—	66.30	89.1
Annual	0.16	19.15	154.43	499.36	159.03	38.17	0.85	—	871.15	99.58

Table 37. Monthly and annual wind energy, kWatt hr/m^2 in each wind speed class, and the average monthly wind power, Watts/m^2, at International Falls.

Month	Wind speed class in miles per hour									Average power
	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	Total	Watts/m^2
	kWatt hr/m^2									
Jan	0.01	1.93	16.05	35.20	18.95	4.51	—	—	76.65	103.1
Feb	0.01	1.85	14.27	30.94	16.73	6.59	—	—	70.39	104.7
Mar	0.01	1.96	15.62	37.72	17.29	7.32	—	—	79.92	107.4
Apr	0.01	1.64	15.49	40.15	29.53	7.93	1.66	—	96.41	133.9
May	0.01	1.77	15.32	41.33	24.71	13.66	—	—	96.80	130.1
Jun	0.02	2.03	15.03	31.64	14.35	4.39	—	—	67.46	93.7
Jul	0.02	2.42	15.36	26.40	11.53	1.83	1.66	—	59.22	79.7
Aug	0.02	2.63	13.72	24.98	8.26	3.66	—	—	53.27	71.5
Sep	0.01	2.32	14.28	29.80	15.18	2.68	—	—	64.27	89.2
Oct	0.01	2.02	16.56	35.04	18.12	5.49	—	—	77.21	103.7
Nov	0.01	1.94	15.87	35.59	12.74	0.85	—	—	67.00	93.1
Dec	0.02	2.19	16.83	29.38	12.80	1.83	—	—	63.05	84.7
Annual	0.16	24.70	184.40	398.17	200.19	60.74	3.32	—	871.65	99.57

Table 38. Monthly and annual wind energy, kWatt hr/m^2 in each wind speed class, and the average monthly wind power, Watts/m^2, at Minneapolis/St. Paul.

Month	Wind speed class in miles per hour									Average power
	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	Total	Watts/m^2
	kWatt hr/m^2									
Jan	0.05	2.30	13.94	35.50	15.24	3.66	—	—	70.69	95.0
Feb	0.04	1.94	13.25	30.52	16.73	7.32	—	—	69.80	104.0
Mar	0.04	1.90	14.93	38.01	25.54	9.02	—	—	89.44	120.5
Apr	0.03	1.42	13.03	44.56	39.12	18.42	1.66	—	118.24	164.4
May	0.04	1.65	14.50	43.21	30.92	11.83	1.66	—	103.81	139.8
Jun	0.04	1.80	15.58	36.79	18.34	4.39	—	—	76.94	106.9
Jul	0.05	2.27	15.83	28.60	8.64	0.85	—	—	56.24	75.7
Aug	0.06	2.37	15.71	24.98	7.42	—	—	—	50.54	68.0
Sep	0.04	2.01	14.74	32.84	16.35	5.24	—	—	71.22	99.0
Oct	0.04	2.02	15.10	34.26	20.61	7.32	—	—	79.05	106.6
Nov	0.03	1.73	14.03	39.07	29.92	13.17	—	—	97.95	136.2
Dec	0.04	2.14	15.45	33.62	14.85	5.49	—	—	71.59	96.3
Annual	0.50	23.55	176.09	421.96	243.68	86.71	3.32	—	955.51	109.37

Table 39. Monthly and annual wind energy, kWatt hr/m^2 in each wind speed class, and the average monthly wind power, Watts/m^2, at Redwood Falls.

Month	Wind speed class in miles per hour									Average power
	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	Total	Watts/m^2
	kWatt hr/m^2									
Jan	0.01	1.18	15.14	58.60	25.99	10.85	3.55	—	115.32	155.0
Feb	0.01	1.24	13.10	51.09	18.62	9.02	3.08	—	96.16	143.2
Mar	0.01	1.21	14.28	58.92	23.94	17.20	3.55	—	119.11	160.1
Apr	0.01	1.15	11.69	62.81	34.30	16.71	5.21	2.97	134.85	158.8
May	0.01	1.54	13.29	56.09	23.50	16.34	3.55	6.36	120.68	162.1
Jun	0.01	1.78	13.86	46.08	15.57	7.07	1.66	—	86.03	119.5
Jul	0.01	2.34	15.23	36.13	7.42	0.85	—	—	61.98	83.4
Aug	0.01	2.22	16.05	36.45	5.76	0.85	—	—	61.34	82.6
Sep	0.02	2.00	14.16	40.76	10.75	4.39	—	—	72.08	100.1
Oct	0.01	1.46	14.84	55.14	19.39	7.32	—	—	98.16	131.9
Nov	0.01	1.61	15.91	44.24	15.57	8.78	—	—	86.12	119.6
Dec	0.01	1.54	15.45	52.16	18.12	8.17	—	—	95.45	128.3
Annual	0.13	19.27	173.00	598.47	218.93	107.55	20.60	9.33	1147.28	128.72

Table 40. Monthly and annual wind energy, kWatt hr/m² in each wind speed class, and the average monthly wind power, Watts/m², at Rochester.

Month	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	Total	Average power Watts/m²
	Wind speed class in miles per hour									
	kWatt hr/m²									
Jan	0.00	0.68	11.78	58.77	75.86	45.37	15.87	—	208.33	280.0
Feb	0.01	0.85	11.46	48.53	61.45	35.25	12.79	2.97	173.31	257.6
Mar	0.01	0.96	13.21	55.31	58.13	39.03	14.21	—	180.86	242.9
Apr	0.00	0.88	10.57	54.28	74.20	45.61	13.74	5.93	205.21	285.2
May	0.01	1.13	13.29	53.73	55.63	30.86	3.55	2.97	161.17	216.9
Jun	0.01	1.31	14.28	51.09	37.90	14.02	1.66	—	120.27	167.2
Jul	0.01	1.92	16.36	43.67	21.44	4.51	—	—	87.91	118.2
Aug	0.01	1.69	18.21	42.74	19.78	1.83	—	—	84.26	113.3
Sep	0.01	1.51	16.16	43.80	29.92	7.07	—	—	98.47	136.7
Oct	0.00	0.96	14.71	57.97	48.21	23.54	3.55	—	148.94	200.3
Nov	0.01	1.03	13.82	54.44	47.88	19.27	6.87	—	143.32	199.1
Dec	0.01	1.00	13.12	55.94	61.45	24.51	3.55	—	159.58	214.4
Annual	0.09	13.92	166.97	620.27	591.85	290.87	75.79	11.87	1771.63	202.65

Table 41. Monthly and annual wind energy, kWatt hr/m² in each wind speed class, and the average monthly wind power, Watts/m², at Sioux Falls.

Month	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	Total	Average power Watts/m²
	Wind speed class in miles per hour									
	kWatt hr/m²									
Jan	0.05	2.12	12.38	34.09	30.92	20.00	7.11	—	106.67	143.3
Feb	0.04	1.68	11.03	35.63	36.13	18.05	—	—	102.56	152.6
Mar	0.03	1.71	11.52	37.23	50.70	39.88	7.11	—	148.18	199.2
Apr	0.03	1.39	11.82	42.72	48.65	39.52	6.87	—	151.00	209.7
May	0.04	1.68	12.68	38.65	30.92	20.00	7.11	—	111.08	149.2
June	0.05	1.87	13.32	33.45	25.54	9.63	—	—	83.86	116.5
Jul	0.07	2.23	14.15	28.13	9.92	—	—	—	54.50	73.2
Aug	0.06	2.41	13.33	26.86	9.92	—	—	—	52.58	70.7
Sep	0.05	1.96	12.19	31.78	21.56	4.39	—	—	71.93	99.9
Oct	0.05	2.04	12.95	33.47	26.38	10.00	—	—	84.89	114.1
Nov	0.04	1.89	12.19	32.99	31.53	29.88	13.74	—	122.26	169.7
Dec	0.05	2.02	12.52	32.84	30.92	14.51	—	—	92.86	124.8
Annual	0.56	23.00	150.08	407.84	353.09	205.86	41.94	—	1182.37	135.24

Table 42. Total monthly and annual (meteorological) wind energy, kWatt hr/m², for a wind power system with a "cut-in" Speed of 8 mi/hr.

Month	Duluth	Fargo	Hibbing	Int'l. Falls	Mpls.-St. Paul	Redwood Falls	Rochester	Sioux Falls
	kWatt hr/m²							
Jan	100.49	137.94	69.63	74.71	68.34	114.13	207.65	104.50
Feb	103.48	120.87	65.88	68.53	67.82	94.91	172.45	100.84
Mar	117.12	147.40	75.69	77.95	87.50	117.89	179.89	146.44
Apr	170.95	191.32	90.05	94.76	116.79	133.69	204.33	149.58
May	143.46	158.11	100.19	95.02	102.12	119.13	160.33	109.36
Jun	90.63	120.11	63.06	65.41	75.10	84.24	118.95	81.94
Jul	76.80	87.15	55.65	56.78	53.92	59.63	85.98	52.20
Aug	71.77	94.34	54.12	50.62	48.11	59.11	82.56	50.11
Sep	100.78	127.40	57.77	61.94	69.17	70.06	96.95	69.92
Oct	119.77	156.43	84.76	75.18	76.99	96.69	147.98	82.80
Nov	157.50	196.92	70.40	65.05	96.19	84.50	142.28	120.33
Dec	120.38	149.74	64.64	60.84	69.41	93.90	158.57	90.79
Annual	1373.13	1687.73	851.84	846.79	931.46	1127.88	1757.62	1158.81

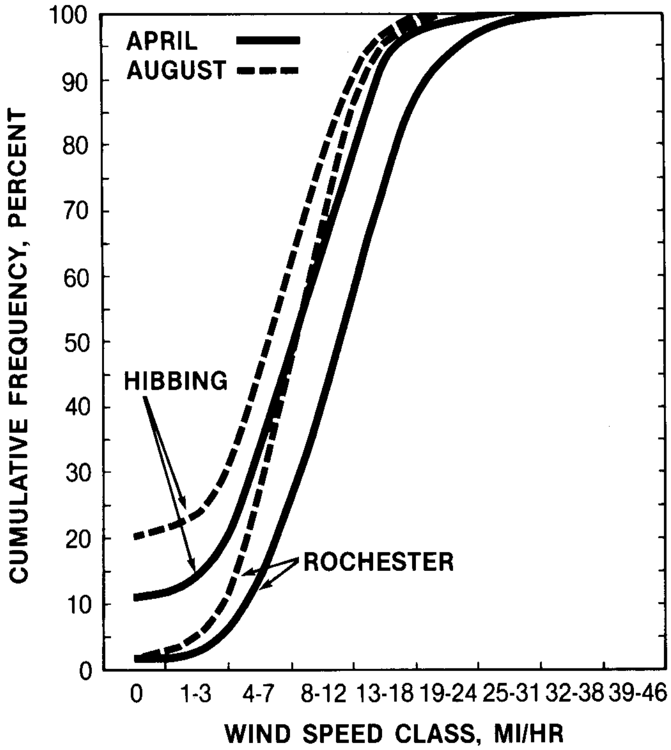

Figure 20. Cumulative frequency of wind speeds at Hibbing and Rochester in April and August. These two stations and two months generally represent the extremes for the state.

Table 43. Average April, August and annual total energy, kWatt hr/m^2, available with a "cut-in" speed of 8 mi/hr and the Betz coefficient taken into account.

Station	April	August	Annual
	kWatt hr/m^2		
Duluth	101.37	42.56	814.27
Fargo	113.45	55.94	1000.82
Hibbing	53.40	32.09	505.14
International Falls	56.19	30.02	502.15
Minneapolis-St. Paul	69.26	28.53	552.36
Redwood Falls	79.28	35.05	668.83
Rochester	121.17	48.96	1042.27
Sioux Falls	88.70	29.72	687.17

Table 44. Average annual percent of winds of at least 19 miles per hour and the percent of the annual total energy they supply.

Station	Percent of winds ≥19 mi/hr	Percent of total energy supplied
Duluth	11.0	51.0
Fargo	14.9	59.2
Hibbing	3.7	22.7
International Falls	4.7	30.3
Mpls.-St. Paul	5.9	34.9
Redwood Falls	5.5	31.1
Rochester	15.3	54.8
Sioux Falls	9.5	50.8

The total or meteorological energy available with a "cut-in" speed of 8 mi/hr for each station is listed in Table 42. On the average the winds at Rochester supply the greatest amounts, due to the site itself, which, as noted in Table 2, results in winds averaging 10-15 mi/hr greater than other stations. Except for sites with special features such as Duluth and Rochester, a greater amount of energy will ordinarily be available for the same given height where the terrain is smooth as illustrated in Figure 2. Consequently, more energy is generally available closer to the earth's surface in the smooth terrain of the Red River valley. Thus, following Rochester in descending order of total energy available (Table 42) are Fargo, Duluth, Sioux Falls, Redwood Falls, and Minneapolis-St. Paul. The least energy available is at Hibbing and International Falls where the annual total is only about 850 kilowatt hr/m^2.

When the cut-in or minimum operating speed (in this case an assumed 8 mi/hr) and the Betz coefficient are considered, the energy available drops dramatically, as shown in Table 43 for April and August and annual totals. If the operating efficiency of the windmill or power plant were also considered, actual energy available would decline further.

As previously stated, all values in this bulletin refer to winds at 20 feet above the surface. The power generated at greater heights could be much greater than indicated here, as shown in Figure 2. The power law wind formula described earlier can be used to estimate wind speeds and thus wind power for heights other than 20 feet. Table 44 illustrates the importance of the higher speed winds to power supply. For example, although winds greater than 18 mi/hr occur only 3.7 and 15.3 percent of the time at Hibbing and Rochester, respectively, they provide 22.7 and 54.8% of the annual total energy.

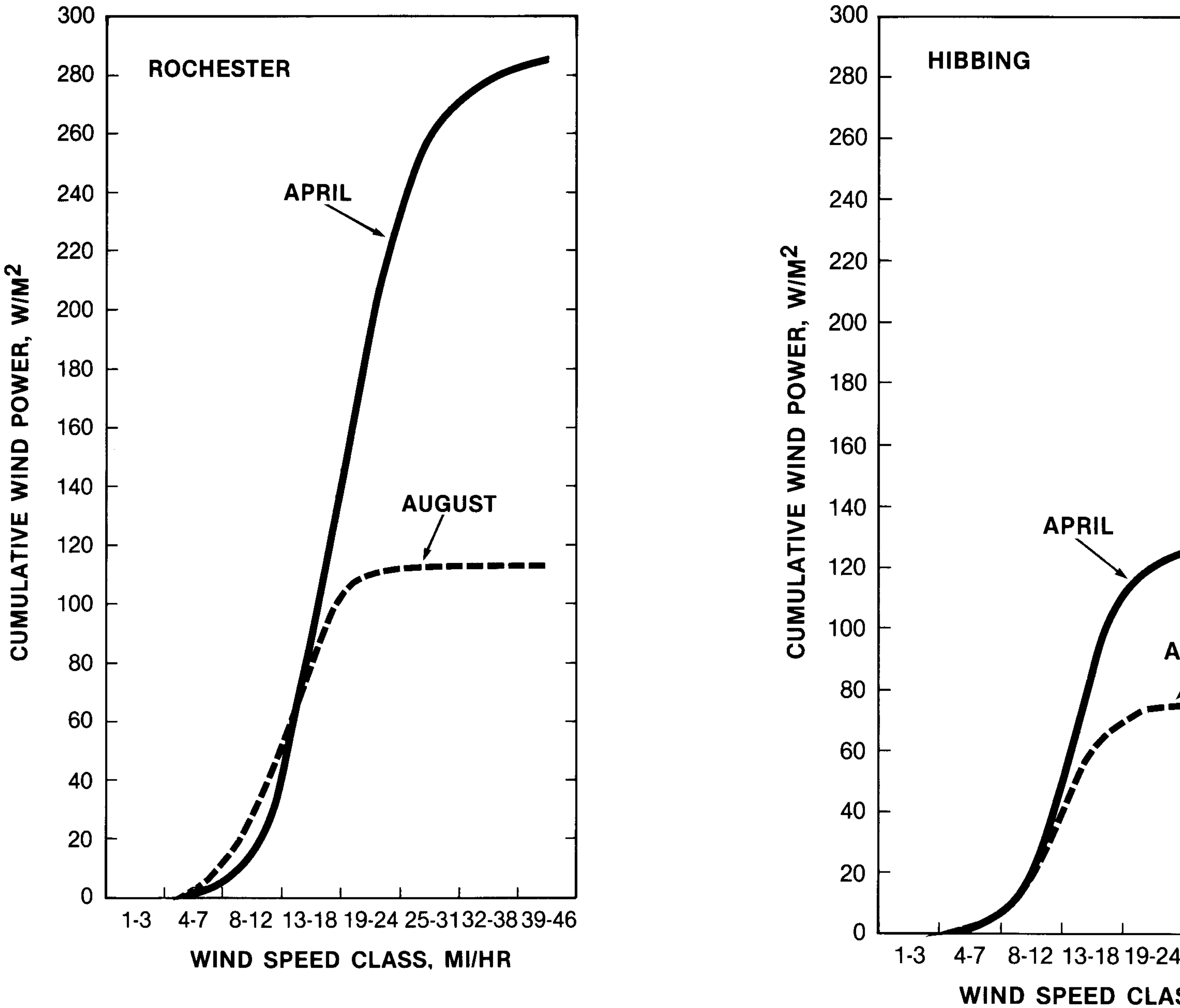

Figure 21. Cumulative wind power at Hibbing and Rochester in April and August. These two stations and tw generally represent the extremes for the state.

VI. Summary and Conclusions

This wind analysis is based upon the 10-year record of eight stations. The one-minute per hour reported speeds and directions were either measured at 20 feet above the earth's surface or calculated for that height using the 1/7 power law formula. All stations but Duluth and Rochester are probably representative of a relatively large area. The Duluth site is greatly influenced by Lake Superior and probably also by the local terrain. The Rochester station is located at the airport, where its elevation above the general surroundings is the probable reason for the higher wind speeds reported there.

It was determined that an acceptable statistical sample (a stable frequency distribution) is obtained with only 5-6 years of a low speed and low variability observation such as that at 0600 hours in any month. In contrast, a 10-year record is probably of insufficient duration for a higher and more variable wind speed observation such as one made at 1500 hours in April. However, for a climatological analysis of monthly data such as this study presents, a 10-year wind speed record of 24 hourly observations per day was found to be of more than sufficient length.

The prevailing Minnesota winds are generally from the northwest in November through April or May at all eight stations and from the south to southeast in the remainder of the year except at Duluth. Easterly winds occur with a high frequency at Duluth in May through August. Lake Superior is believed largely responsible for this, though the local topography may play a part also.

The wind roses, limited to winds of 8 mi/hr or greater, exhibit a marked monsoon or seasonal wind shift effect already noted with the prevailing winds. This causes a bimodal frequency of wind direction in the annual wind roses, a condition most marked at Fargo and weakest at Hibbing and International Falls.

The mean wind maximum occurs in April, except at Hibbing, which shows a May maximum. The minimum mean speed occurs in either July or August at all stations. Speeds of 3 mi/hr or less are essentially a summer and a nighttime feature.

Vector winds, resultant winds, and wind constancy were calculated for each station. At Duluth, although the wind roses and prevailing winds are generally easterly, the vector winds are not and they usually override or "mask" the lower-speed easterlies.

At almost all stations winds of 8-12 mi/hr are the most common. Because wind power is a function of the cube of the wind speed there is essentially an inverse relationship between wind power associated with a given speed and the frequency of occurrence of that speed.

Wind speeds of 8 mi/hr and greater occur on the average about 53% of the time annually at International Falls, increasing to 61% at Hibbing and Sioux Falls, 63% at Minneapolis-St. Paul, 72-75% at Redwood Falls, Duluth and Fargo, and nearly 82% at Rochester.

The average annual meteorological power of winds 8 mi/hr or greater is highest at Rochester and Fargo where they supply approximately 200 Watts/m^2, followed by Duluth with about 160 Watts/m^2, and Sioux Falls and Redwood Falls with around 130 Watts/m^2 each. If the Betz coefficient is considered, the monthly average wind power is reduced to a maximum of about 120 Watts/m^2 at Rochester and a minimum of 59 Watts/m^2 at International Falls. This does not take into account a further reduction ranging from 20-65% that would result if the efficiency of the power system itself were caclulated. Even though these values are only for a height of 20 feet, it is apparent that there is not a wealth of available wind power in much of Minnesota.

This bulletin has emphasized the systematic or climatological variability in wind speed, and consequent wind energy and power. In addition to the systematic differences there is also great non-systematic (unpredictable) variability between hours, days, months and even years. An indication of the variability inherent in wind speeds was shown by a brief analysis of the Minneapolis-St. Paul station data. It was found that a 30-45% variation occurred between a decade's monthly mean speeds and variation of 40% between two Aprils in successive years. Mean annual speeds showed an interannual variation of 20%.

Based on current technology, wind should not be considered a reliable source of power in Minnesota. Rather, across most of the state it should be viewed only as a supplemental source.

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