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BEHAVIOR OF WINDS IN THE LOWEST 1500 FEET IN CENTRAL OKLAHOMA: JUNE 1966 - MAY 1967

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FOREWORD

The work reported here has been supported by WKY Television Systems, Inc., and by the National Aeronautics and Space Administration. The transmitting tower of WKY-TV in Oklahoma City was made available to the National Severe Storms Laboratory for the installation of meteorological sensors through the cooperation of the management and engineers of WKY Television Systems, Inc. NASA's financial support assisted in the purchase and installation of conduit and temperature and wind sensors on the tower, and has been a continuing substantial aid to investigations.

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ABSTRACT

A television tower in northern Oklahoma City, Oklahoma, is equipped with wind and temperature sensors at 6 levels ranging from 146 ft to 1458 ft above the base of the tower. Data are also obtained from a nearby tower 23 ft above ground level and 40 ft above the base of the television tower. A one year data sample consisting of the mean wind speed and direction and the highest recorded gust during one 5-minute period per hour was used in this study.

The annual arithmetic mean wind speed increases from 8.1 kt at the surface to 18.7 kt at the top level. The annual mean speeds below the level at 296 ft are lowest at night and highest during the day, and the speeds above this level are lowest during the day and highest at night. Most of the speed change occurs in short time periods shortly after sunrise and near sunset.

Annual relative frequency distributions of wind direction are bimodal with most of the winds being either southerly or northerly. The primary peak occurs in the 10° sector centered on 180° at the lowest 3 levels and at 190° at the upper 4 levels. The direction veers with height between the surface and top levels 80% of the time. The higher the wind speed, the more likely the direction is to be southerly.

The direction of the annual resultant (vector mean) wind is 181° at the lowest 4 levels and veers with height to 198° at level 6. The resultant directions veer significantly with height between 1700-1000 CST and veer least with height during midday. Winds at all levels veer with time between 2100 and approximately 1100 CST and then back with time during the remaining hours.

The variability of wind speed and direction is investigated using transition matrices (probabilities for change with time) and wind persistence (number of consecutive observations the winds blow from a given sector).

Wind shear speed is greatest in the lowest layer and least in the sixth layer. Speed shear is dominant over direction shear in the lower 3 layers and a combination of speed and direction shear occurs in the upper 3 layers. The speed shear decreases rapidly near sunrise, reaches a minimum in early afternoon, and increases rapidly near sunset. Shear is greater in all layers at night than during the day.

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1. INTRODUCTION

Towers equipped with meteorological instruments are operated at several locations in the United States (U.S. Dept. of Commerce, 1969). These towers range in height from tens of feet to near 1600 ft above the ground and yield data that have applications to many types of studies. The National Severe Storms Laboratory (NSSL) at Norman, Oklahoma, has collected wind and temperature data at 7 levels at the 1602 ft television tower of WKY-TV in Oklahoma City since 1966, primarily to investigate mesoscale features associated with thunderstorms. The tower is located within a surface and upper air network that is also designed to gather data on thunderstorms. Radar coverage of this area is provided by NSSL and the U.S. Weather Bureau at Oklahoma City.

This report investigates the general statistical properties of wind data at the tower to provide a base for severe storm studies and theoretical boundary layer studies. In addition, this study should be of practical value to groups, such as NASA and the aviation industry, that are interested in the winds in the lowest 1500 ft. The data used in this report consist of the average wind speed, the average wind direction, and the peak gust, the highest recorded speed, observed during 5-min periods centered at the start of each hour during the 12 months from 1 June 1966 to 31 May 1967. Occasional equipment outages resulted in some missing data. Missing wind directions account for 3.1% of the total possible observations (8760) at the surface level and for less than 1.5% of the observations at the other levels. Less than 0.75% of the wind speeds are missing at any level. The data were reduced from strip charts to digital form with the aid of a Benson-Lehner Oscar Model K trace reader.

The strip chart record for approximately a 90-min period at the surface level is shown in figure 1. This sample contains many rapid changes of wind speed and direction but none that are extreme. The digitized values of mean speed, mean direction, and peak gust are shown at 1200 and 1300 CST.

2. TOWER SITE AND INSTRUMENTATION[1]

The WKY-TV tower is about 6 n miles north of downtown Oklahoma City and about 20 n miles north of NSSL. This area of Oklahoma City is relatively

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[1]See Carter (1970) and Sanders and Weber (1970) for further details.

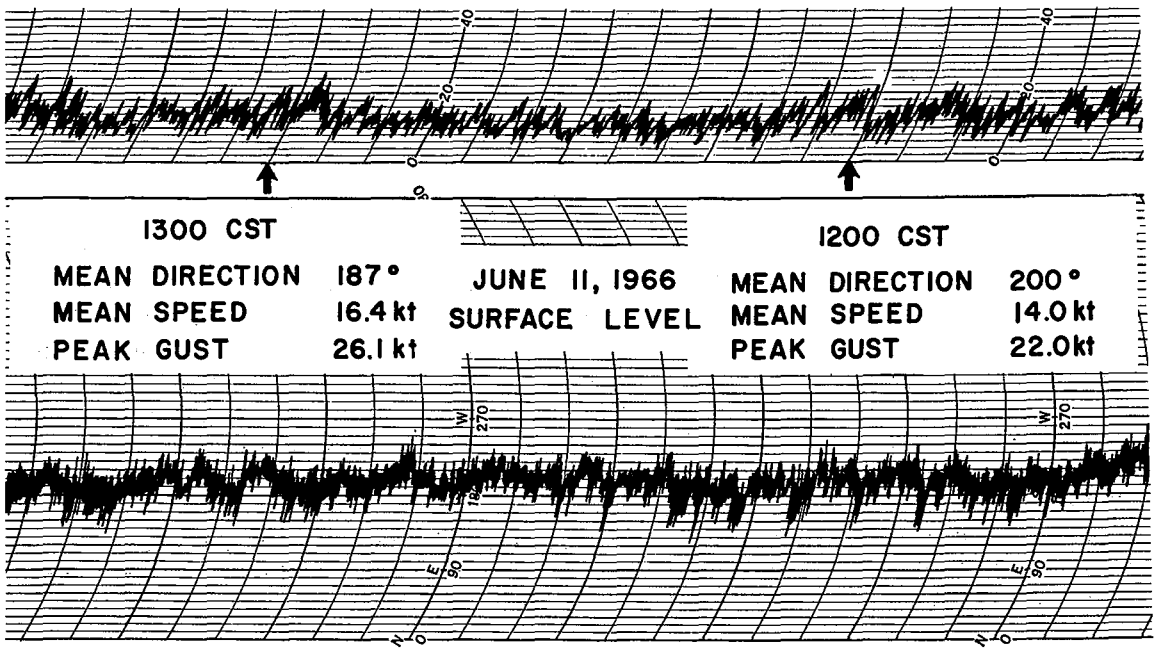


Figure 1. An example of strip chart data at the surface level of the WKY tower on 11 June 1966. The digitized values of mean speed, mean direction, and peak gust are shown for 2 different 5-min periods.

undeveloped with open fields and several small ponds and wooded gullies on a gently rolling terrain (fig. 2). The base of the tower is at 1148 ft MSL and is in a shallow gully which is free of trees. It was felt that the effect of this depression and that of the transmitter building 175 ft southwest of the tower would cause wind measurements near the base of the tower to be unrepresentative of ambient conditions. For this reason, the surface winds are measured on a 23 ft tower at a ground elevation 17 ft higher and 250 ft west northwest of the base of the tower. This location is 200 ft north of the transmitter building. The wind sensor is about 10 ft higher than the highest section of the building.

The television tower is of uniform triangular cross section, 10 ft on a side, from its base to 1515 ft above the ground. Two legs of the tower are oriented north-south, and the third leg is to the west. Bendix Friez Aerovane wind sensors with three blade propellers and Yellow Springs linearized thermistor composite-type temperature sensors are installed at the surface level and at the following six levels above the ground on the tower: (1) 146 ft, (2) 296 ft, (3) 581 ft, (4) 873.5 ft, (5) 1166 ft, and (6) 1458.5 ft.

3. DATA ACCURACY

The wind sensors are mounted 10 ft south of the west leg of the tower (point A in fig. 3). Wind tunnel experiments were made by Gill et al.

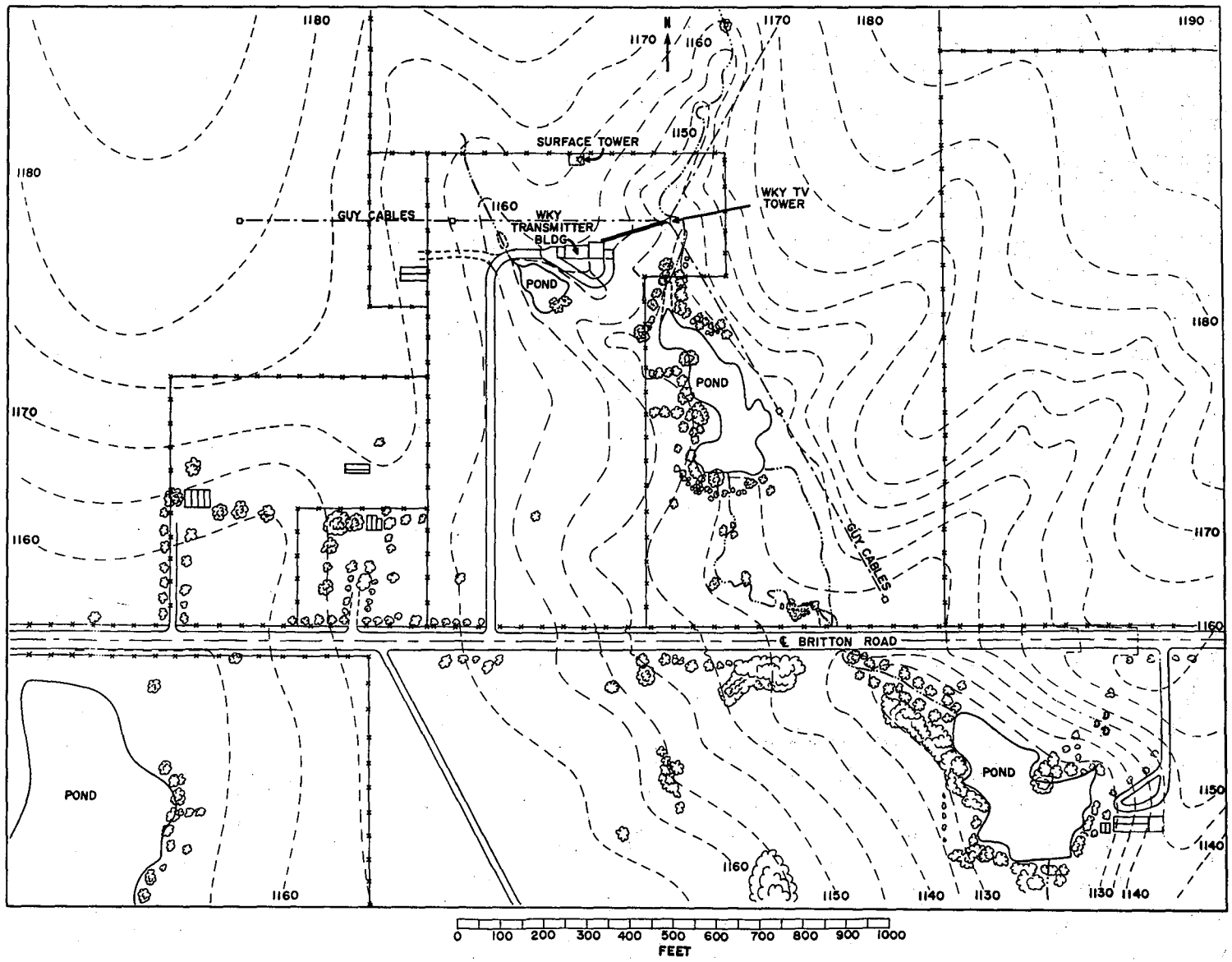


Figure 2. Plan view of NSSL-WKY meteorological tower facility.

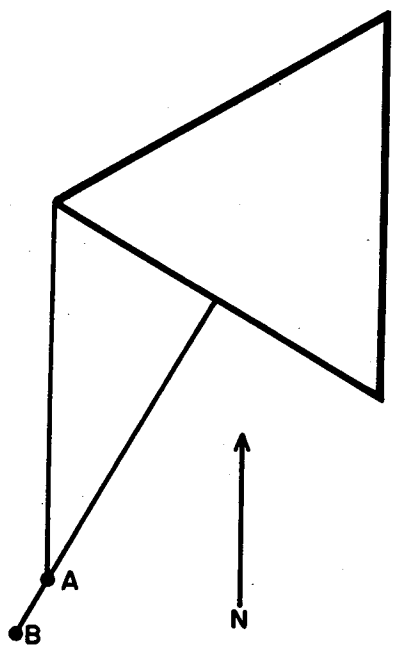


Figure 3. Position of wind sensor at WKY Tower (point A) and position of wind sensor in study by Gill, Olsson, and Suda (point B).

(1966, 1967) for a model tower similar to the WKY-TV tower. Their measurements apply at point B, which is 10 ft from the middle of one side of the tower. Point A is along the line between point B and the middle of the southwest face of the tower and is 1.34 ft closer to the tower than is point B. Consequently, the study by Gill et al. provides a good estimate of the effects of the tower on the measured wind speeds.

Wind speeds are reduced by more than 10% in the interval between 0° and 60° (12.5% of the observations were in this interval), by more than 20% in the interval 22°-38°, and by a maximum of 40% at 30°. Wind speeds are enhanced by slightly more than 10% in small intervals near 345° and 75°. No correction for this tower effect was applied to the data as the effect is slight for analyses of wind speed that include all directions. The only distributions in this study that may be affected significantly are those of wind direction according to wind speed (sec. 6.5).

The reduced data contain the effects of several types of errors. These include the accuracy of the instruments and the accuracy of reading the strip charts and estimating the mean speeds and directions. It is subjectively felt that the accuracy of the data is about $\pm$ 1 kt and $\pm$ 2°.

4. COMPARISON OF TOWER DATA WITH DATA FROM THE OKLAHOMA CITY WEATHER BUREAU

Wind data from the WKY-TV tower surface site were compared with climatological data from the Oklahoma City Weather Bureau Airport Station (OKC) to determine how well statistics based upon this 12-month period of tower data approximate long term values. This comparison is based upon climatological data for OKC for the period 1951-1960 contained in U.S. Dept. of Commerce (1963).

The Weather Bureau Airport Station is 11 n miles south-southwest of the tower with most of Oklahoma City between the two observation sites. Wind instruments were located at a height of 70 ft above ground level (AGL) from 1951 until 20 May 1954 when they were moved and lowered to 55 ft AGL. Thus, the observations at OKC were made at a level higher than the surface level at the tower, which is at 23 ft AGL and 40 ft above the base of the tower.

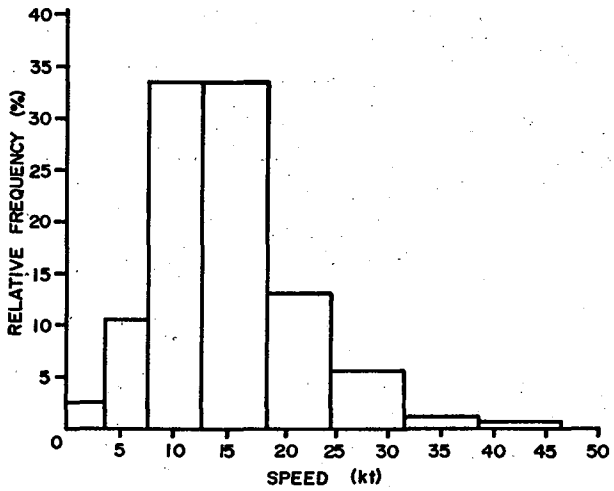


Figure 4A. Relative frequency distribution of wind speed at the Oklahoma City Weather Bureau for the period 1951-1960.

Relative frequency distributions of wind speed for the climatological data, which have an arithmetic mean of 12.2 kt, and for the tower, which have an arithmetic mean of 8.1 kt, are shown in figures 4A and 4B. Speed intervals are those used by the U.S. Weather Bureau (i.e., 0-3 kt, 4-7 kt, 8-12 kt, 13-18 kt, 19-24 kt, 25-31 kt, 32-38 kt, 39-46 kt, and greater than 46 kt). Since the wind speed increases with height at the tower in the mean, part of the difference between the mean speeds is caused by the difference in the height above ground of the anemometers. However, this can account for only part of the difference because the mean speed at level 1 (146 ft above the tower base) is 11.3 kt, which is less than the climatological mean.

The climatological mean speed by month (fig. 5) shows a steady increase from the minimum in July and August to the maximum in April with a rapid decrease back to the minimum in summer. The monthly mean wind speeds at the surface level at the tower have the same trend as do the climatological

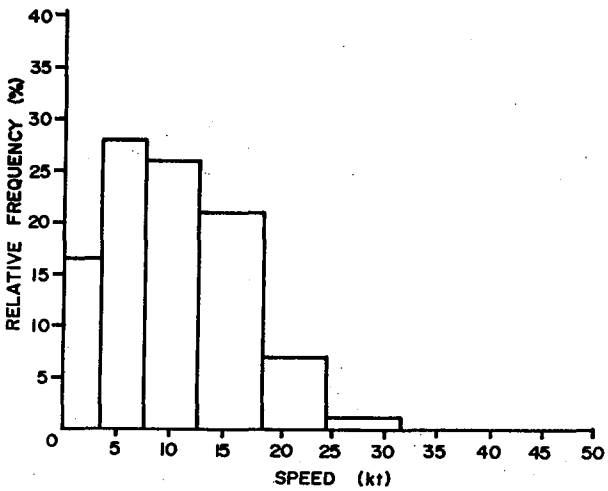


Figure 4B. Relative frequency distribution of wind speed at the surface level at the WKY tower for the period 1 June 1966-31 May 1967.

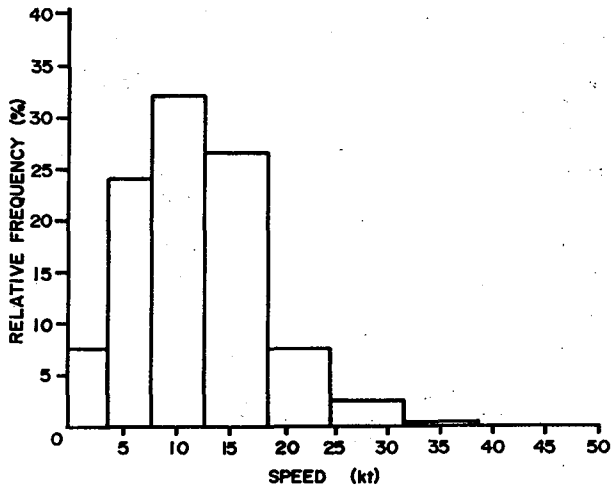


Figure 4C. Relative frequency distribution of wind speed at the Oklahoma City Weather Bureau for the period 1 June 1966-31 May 1967.

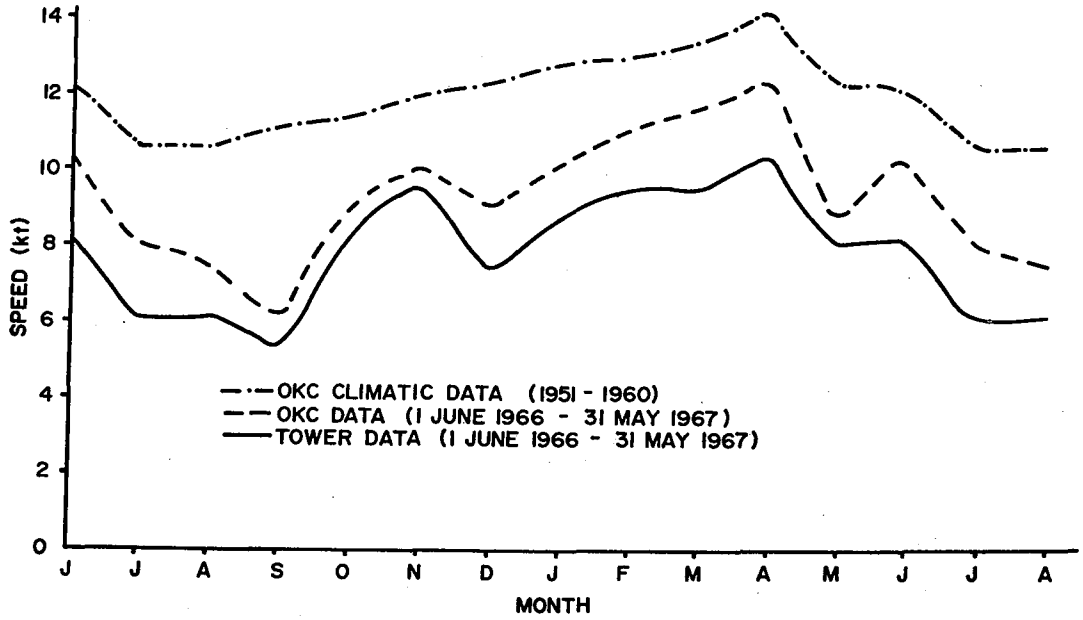


Figure 5. Monthly mean wind speed for the Oklahoma City climatic data (1951-1960), the Oklahoma City Weather Bureau (1 June 1966-31 May 1967), and the surface level at the WKY tower (1 June 1966-31 May 1967).

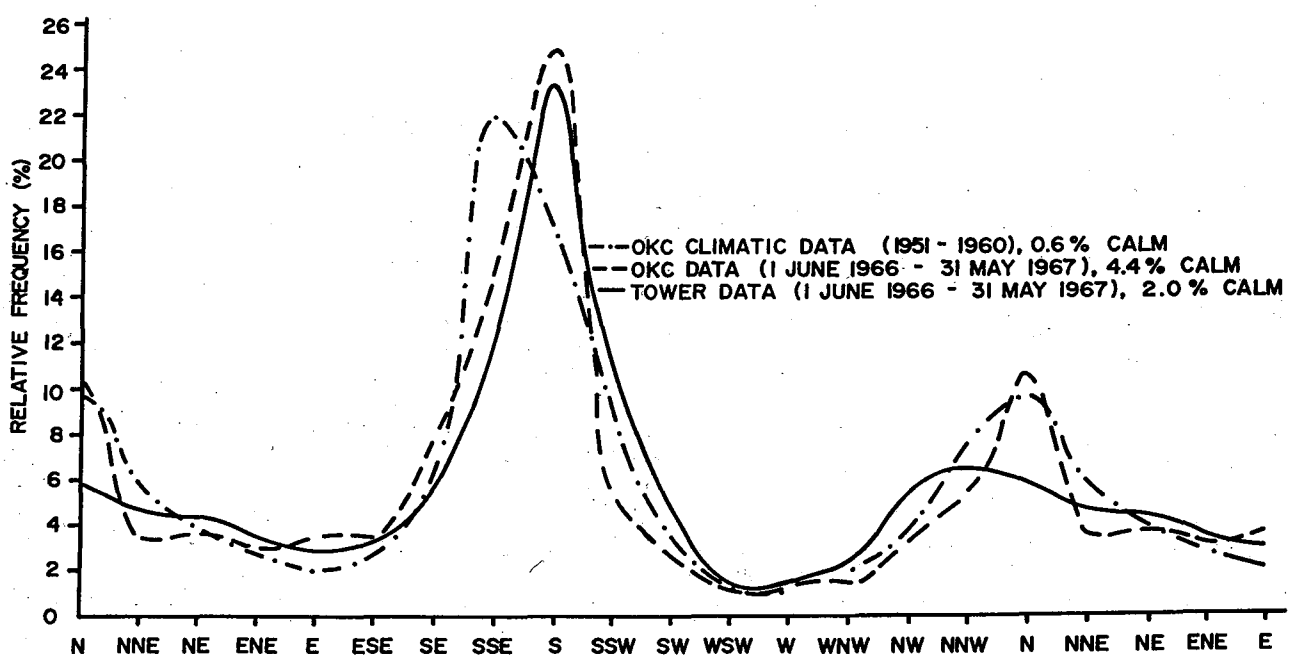


Figure 6. Relative frequency distributions of wind direction at the Oklahoma City Weather Bureau (1951-1960), the Oklahoma City Weather Bureau (1 June 1966-31 May 1967), and the surface level at the WKY tower (1 June 1966-31 May 1967).

speeds but are lower and more variable. However, greater variability would be expected in the smaller sample presented by the tower data.

The relative frequency distributions of wind direction for the 12 months of tower data and the OKC climatic period (fig. 6) are very similar except that the most frequent direction is south-southeast for the climatic period and is south for the tower data. The frequency distribution for approximately the southern semicircle of the OKC data is shifted 10°-20° counterclockwise from that at the tower.

In 1965 the wind instruments at OKC were moved and lowered to 20 ft AGL, 3 ft below the height of the surface level at the tower. Thus, a good comparison can be made between the sites. The relative frequency distribution of wind speed and the mean speed by month are shown in figure 4C and figure 5, respectively, for OKC for the year 1 June 1966-31 May 1967. The annual arithmetic mean wind speed for OKC was 9.5 kt, some 1.4 kt greater than that at the tower. Month to month variations in the mean speed were similar to those observed at the WKY surface level during this 1 year period. The annual relative frequency distribution for wind direction (fig. 6) indicated that both OKC and the tower surface level had the maximum frequency in the 180° sector (22.5° sector centered on south), although there is still a tendency for more winds east of south in the OKC data and more west of south in the WKY data.

Thus, there is much better agreement between the year's data at OKC and the tower than between the OKC climatology and the tower. The remaining differences are due, perhaps, to local terrain effects or to effects of the city, which lies between the two sites.

5. CHARACTERISTICS OF THE WIND SPEED

5.1 Monthly and Annual Relative Frequency Distributions

Relative frequency distributions of the wind speed, the arithmetic mean wind speed, the standard deviation, skewness, and kurtosis were calculated for each level by month and for the year. Comparisons are made with the normal or Gaussian distribution, the fundamental frequency distribution of statistical analysis.

A continuous variable X is said to have a normal distribution if it possesses a probability density function f(X), which satisfies the equation:

$$f(X) = \frac{1}{\sigma\sqrt{2\pi}} \; e^{-\frac{(X-\mu)^2}{2\sigma^2}} , \quad (-\infty < X < \infty) , \tag{1}$$

where μ and σ are the arithmetic mean and the standard deviation of the population, respectively (Brooks and Carruthers, 1953). The variable X may be expressed in terms of a standardized variable, $Z = (X-\mu)/\sigma$, so that Z is normally distributed with a mean of zero and a standard deviation of one (fig. 7).

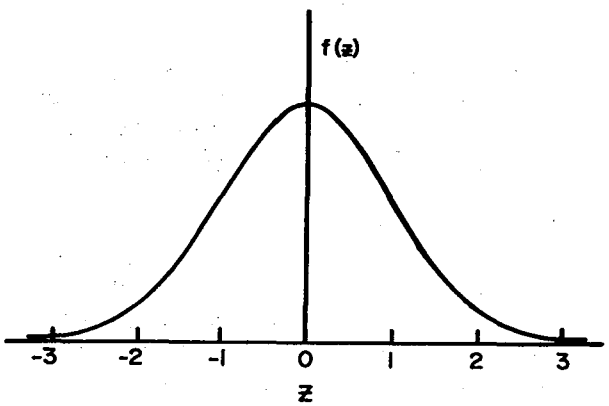


Figure 7. The normal distribution.

The arithmetic mean of a set of observations is the sum of the observations divided by the number of observations. The arithmetic mean wind speed for month m at a given level is

$$V_m = \frac{1}{n_d} \sum_{d=1}^{n_d} \left(\frac{1}{24} \sum_{h=0}^{23} V_h\right) , \qquad (2)$$

where V_h represents one observation of wind speed at hour h (h = 0, 23) during day d (d = 1, n_d) of month m (m = 1, 12). The number of days in a month is n_d. The quantity in parentheses is the arithmetic mean wind speed for 1 day in month m.

The arithmetic mean wind speed for the year at a given level is

$$V_y = \frac{1}{12} \sum_{m=1}^{12} \left[\frac{1}{n_d} \sum_{d=1}^{n_d} \left(\frac{1}{24} \sum_{h=0}^{23} V_h\right) \right] = \frac{1}{12} \sum_{m=1}^{12} V_m \quad . \qquad (3)$$

Moments of the distributions will be used to describe the distributions in terms of the mean. The moments of a set of observations are defined in terms of deviations from an arbitrary origin (chosen here to be the arithmetic mean). The kth moment about the annual arithmetic mean V_y is

$$M_{yk} = \frac{1}{12} \sum_{m=1}^{12} \left\{ \frac{1}{n_d} \sum_{d=1}^{n_d} \left[\frac{1}{24} \sum_{h=0}^{23} (V_h - V_y)^k \right] \right\} , \qquad (4)$$

and the kth moment about the monthly arithmetic mean V_m is

$$M_{mk} = \frac{1}{n_d} \sum_{d=1}^{n_d} \left[\frac{1}{24} \sum_{h=0}^{23} (V_h - V_m)^k \right] . \qquad (5)$$

The first moment is the algebraic mean of the deviations from the mean and is zero. Thus, the first moment expresses a basic property of the arithmetic mean.

The second moment is the mean of the squares of the deviations and is called the variance. The square root of the second moment is called the standard deviation, a principal measure of dispersion in statistics. For a normal distribution, 68.27% of the observations are within 1 standard deviation, 95.45% are within 2 standard deviations, and 99.73% are within 3 standard deviations of the mean.

The third moment is the algebraic sum of the cubes of the deviations divided by the number of observations. The third moment divided by the cube of the standard deviation is called skewness and is a measure of the symmetry of a frequency distribution. When a frequency distribution decreases steeply to the left of the mean and gradually to the right, it is said to be "skewed to the right" or to have "positive skewness." When the reverse is true, the distribution is said to be "skewed to the left" or to have "negative skewness." The skewness of a symmetric distribution such as the normal distribution is zero.

The fourth moment is the mean of the fourth powers of the deviations. The fourth moment divided by the fourth power of the standard deviation is called kurtosis and is a measure of the relative sharpness or flatness of the distribution. When a curve has a relatively high peak, it is called leptokurtic, and when it has a relatively low peak, it is called platykurtic. The normal distribution is called mesokurtic and has a kurtosis value of 3.0.

The frequency distributions of the wind speed for the year (figs. 8A-G) show that both mean and range, the difference between the maximum and minimum values, increase with height from the surface level to the top of the tower. The mean values in knots in order of increasing height are: 8.1, 11.3, 13.7, 15.6, 17.2, 18.6, and 18.7 (table 1 and figs. 8A-G). The vertical profile for the annual data is shown in figure 9 as are the profiles by season (summer: June-August; fall: September-November; winter: December-February; and spring: March-May). The seasonal means increase at all levels from summer through spring. The winter profile approximates the profile for the year. Since the mean wind speed becomes nearly constant with height at the top of the tower, frictional effects must be small at the top of the tower.

The ratio of the standard deviation of the annual arithmetic mean wind speed to the annual arithmetic mean wind speed is between 0.47 and 0.64. Skewness, which is positive at all levels, first decreases with height from a value of 0.63 at the surface to a minimum of 0.20 at level 3 and then increases to 0.65 at level 6 for the annual frequency distributions. All levels are "flatter" than the normal curve, except level 1 that has a kurtosis value of 3.04; however, nine of the monthly values for level 1 are platykurtic.

Monthly mean wind speeds show considerable variation from month to month (table 1 and fig. 10). The variation is greatest at the higher levels. The speeds decreased from June to September 1966 at all levels and then increased in October and November. Mean wind speeds for December 1966 were lower than those of the surrounding months. The mean wind speeds increased from February 1967 to a peak in April and then began to decrease. The mean wind speed tended to increase with height to the top of the tower during winter and to reach a maximum at level 5 during the summer.

Monthly values of the ratio of the standard deviation to the mean wind speed varies from 0.34 in July at level 2 to 0.69 in September at the surface level. The surface level and levels 5 and 6 are skewed to the right (table 1) for all months; levels 1, 2, 3, and 4 are skewed to the left for a few months. The skewness ranges from -0.31 during July at level 2 to 1.10

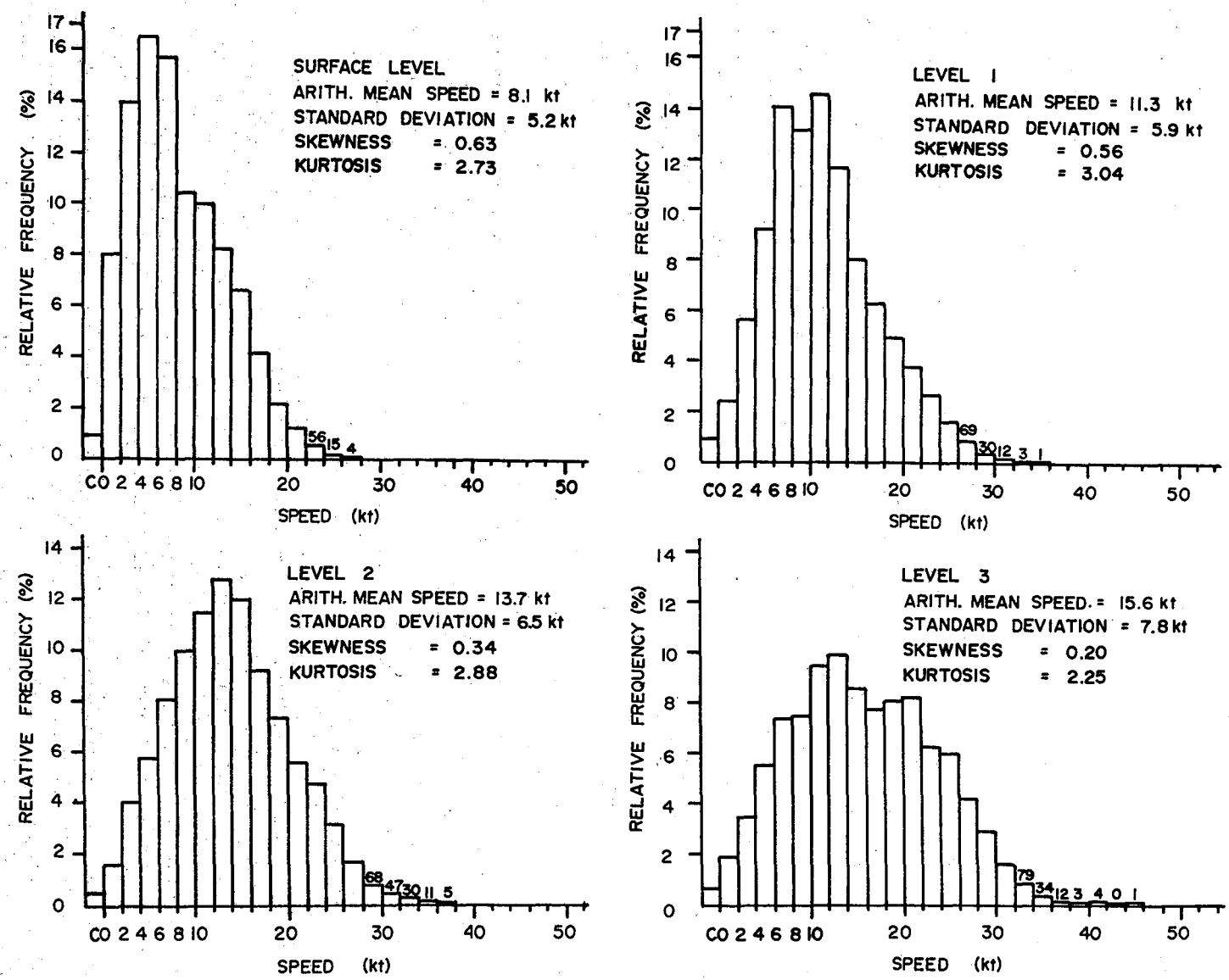
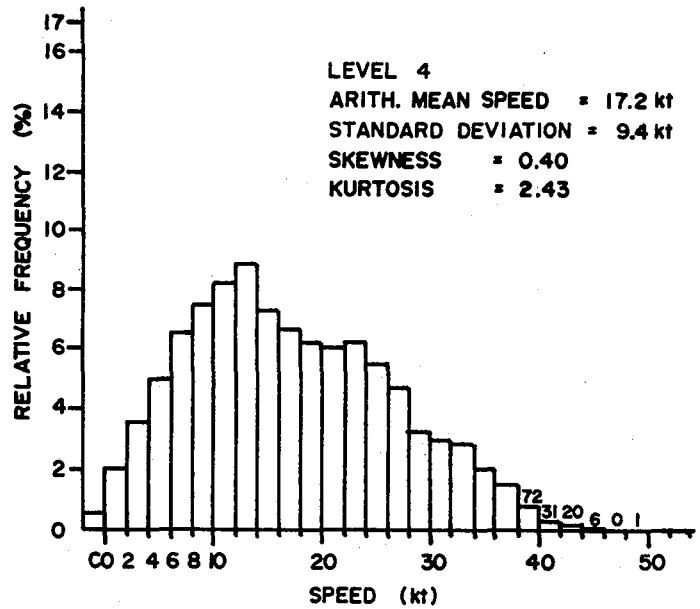
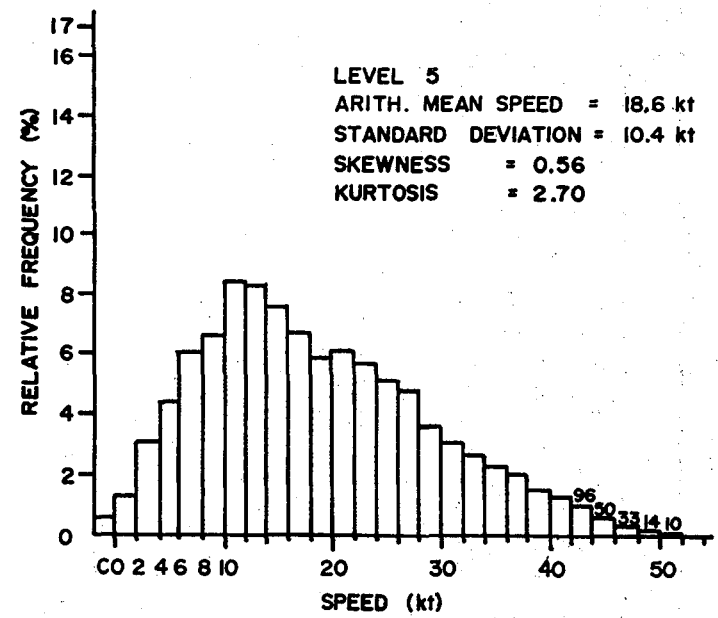


Figure 8A-D. Annual relative frequency distributions of wind speed in 2 kt intervals for A) surface level, B) level 1, C) level 2, and D) level 3. The arithmetic mean speed, standard deviation, skewness, kurtosis, and the number of events for categories with less than 1% of the events are shown.





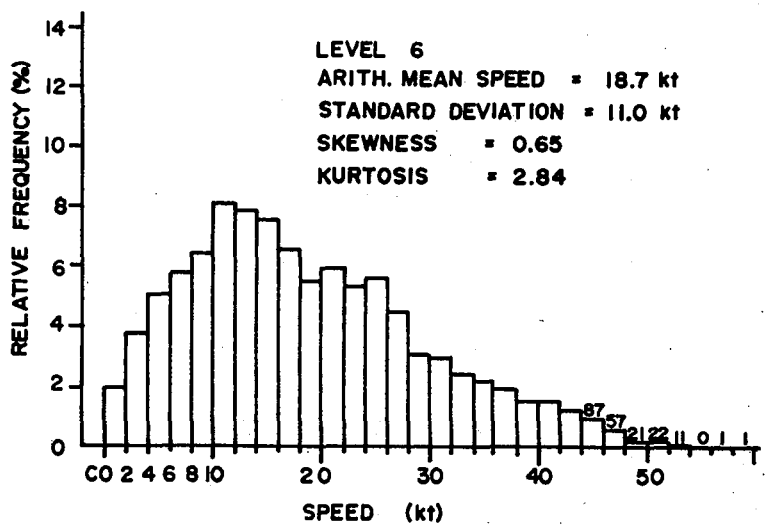


Figure 8E-G. Annual relative frequency distributions of wind speed in 2 kt intervals for E) level 4, F) level 5, and G) level 6. The arithmetic mean speed, standard deviation, skewness, kurtosis, and the number of events for categories with less than 1% of the events are shown.

TABLE 1. ARITHMETIC MEAN WIND SPEED, STANDARD DEVIATION OF THE ARITHMETIC MEAN WIND SPEED, AND SKEWNESS AND KURTOSIS OF THE MONTHLY AND ANNUAL RELATIVE FREQUENCY DISTRIBUTIONS OF WIND SPEED.

LEV	HEIGHT ABOVE BASE OF TOWER		ARITHMETIC MEAN WIND SPEED (KT)												
	FT	M	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	YEAR
6	1458.5	444.6	19.1	15.9	14.5	12.5	19.5	22.8	16.6	21.3	19.5	20.7	24.6	18.1	18.7
5	1166.0	355.4	19.8	16.0	14.8	13.0	19.7	22.1	16.3	20.6	19.3	20.8	23.4	18.0	18.6
4	873.5	266.2	18.7	15.2	13.5	11.6	17.9	20.5	15.1	18.9	17.9	18.9	21.6	16.7	17.2
3	581.0	177.1	16.7	13.2	12.3	10.5	16.5	17.6	13.7	17.2	16.3	17.7	19.6	15.5	15.6
2	296.0	90.2	14.7	11.3	11.1	9.4	14.5	15.5	12.7	15.4	14.9	15.3	16.1	13.4	13.7
1	146.0	44.5	11.8	9.3	9.0	7.6	11.9	13.2	10.7	12.2	12.3	12.3	13.8	11.3	11.3
SFC	40.0	12.2	8.2	6.1	6.1	5.4	8.3	9.5	7.5	8.8	9.5	9.5	10.4	8.1	8.1
LEV	HEIGHT ABOVE BASE OF TOWER		STANDARD DEVIATION OF THE ARITHMETIC MEAN WIND SPEED (KT)												
6	1458.5	444.6	9.8	7.3	8.0	7.6	11.8	11.7	10.9	12.3	12.5	10.9	11.2	10.4	11.0
5	1166.0	355.4	9.2	7.4	7.8	7.6	11.3	11.0	10.1	11.9	11.8	10.5	10.1	10.1	10.4
4	873.5	266.2	7.9	6.8	7.0	7.4	10.2	10.0	9.3	10.6	10.8	9.2	8.3	9.0	9.4
3	581.0	177.1	6.7	5.1	5.6	6.3	8.6	8.1	7.6	8.7	9.0	7.6	6.8	7.7	7.8
2	296.0	90.2	5.7	3.8	4.5	5.2	7.1	6.8	6.2	7.4	7.8	6.4	6.0	5.9	6.5
1	146.0	44.5	5.7	3.5	3.9	4.2	6.4	6.4	5.5	6.7	6.9	5.9	6.0	5.3	5.9
SFC	40.0	12.2	4.7	3.2	3.4	3.7	5.6	5.4	4.8	5.8	6.4	5.2	5.0	4.8	5.2
LEV	HEIGHT ABOVE BASE OF TOWER		SKEWNESS OF THE FREQUENCY DISTRIBUTION OF WIND SPEED												
6	1458.5	444.6	0.59	0.21	0.61	1.05	0.69	0.22	0.60	0.50	0.59	0.34	0.24	0.55	0.65
5	1166.0	355.4	0.46	0.25	0.59	1.10	0.72	0.16	0.54	0.38	0.48	0.37	0.24	0.53	0.57
4	873.5	266.2	0.21	0.12	0.53	1.08	0.45	-0.12	0.50	0.20	0.31	0.21	0.14	0.46	0.40
3	581.0	177.1	0.09	-0.24	0.32	0.61	0.49	-0.20	0.32	-0.05	0.15	0.00	-0.03	0.15	0.20
2	296.0	90.2	0.32	-0.31	0.35	0.25	0.39	0.05	0.21	0.08	0.26	0.17	0.14	0.14	0.34
1	146.0	44.5	0.64	-0.07	0.40	0.44	0.61	0.13	0.53	0.37	0.34	0.35	0.23	0.32	0.56
SFC	40.0	12.2	0.50	0.33	0.52	0.94	0.69	0.18	0.69	0.57	0.46	0.20	0.06	0.55	0.63
LEV	HEIGHT ABOVE BASE OF TOWER		KURTOSIS OF THE FREQUENCY DISTRIBUTION OF WIND SPEED												
6	1458.5	444.6	2.73	2.21	2.90	4.50	2.74	2.11	2.68	2.46	2.67	2.59	2.30	2.73	2.84
5	1166.0	355.4	2.55	2.19	2.86	4.67	2.60	2.09	2.45	2.30	2.57	2.57	2.35	2.70	2.70
4	873.5	266.2	2.37	2.23	2.79	4.66	2.13	2.16	2.31	2.03	2.18	2.42	2.38	2.65	2.43
3	581.0	177.1	2.60	2.23	3.34	3.21	2.14	2.25	2.18	1.99	2.00	2.41	2.39	2.53	2.25
2	296.0	90.2	3.32	2.70	4.42	2.58	2.90	2.44	2.51	2.43	2.33	2.61	2.26	2.84	2.88
1	146.0	44.5	3.25	2.79	4.24	2.94	3.28	2.39	2.94	2.63	2.27	2.63	2.23	2.92	3.04
SFC	40.0	12.2	2.96	2.83	3.14	4.11	2.89	2.06	2.83	2.41	2.24	2.12	2.24	2.72	2.73

during September at level 5. Most of the monthly frequency distributions are "flatter" than the normal curve. At each level, from 9 to 11 months are platykurtic.

5.2 Cumulative Relative Frequency Distributions for Speed and Peak Gust

Cumulative relative frequency distributions for wind speeds at each level were calculated from the annual relative frequency distributions of wind speeds and are listed in table 2. Values are rounded to the nearest 0.5 kt. At the surface level 95% of the wind speeds exceeded 2.5 kt, 50% (the median value) exceeded 9.0 kt, 5% exceeded 19.5 kt, and 1% exceeded 23.5 kt. Wind speeds increase with height to the top of the tower at the

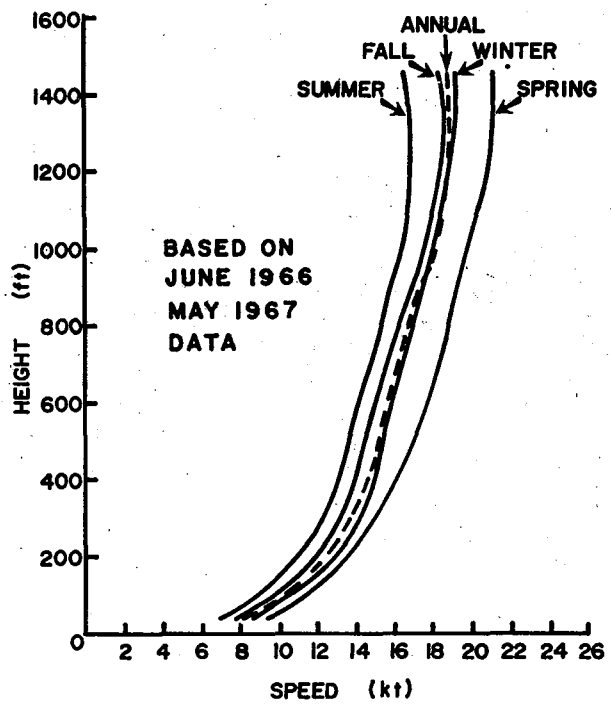


Figure 9. Annual and seasonal vertical profiles of the arithmetic mean wind speed.

95% and 99% levels and to level 5 at the 50% level, which has the same value at level 6. There is little change with height at the 5% level.

Cumulative relative frequency distributions for peak gusts were calculated in a similar manner (table 3) and exhibit a pattern similar to that of the wind speed. Values of wind speed and peak gust are essentially the same at level 6.

5.3 Change of Wind Speed with Time

The time variability of the tower wind speeds was examined on an annual basis. Thirteen categories of wind speed (calm, 0.1-4.9 kt, 5.0-9.9 kt, ..., 55.0-59.9 kt) were used. Matrices called contingency tables were constructed for speed changes for time lags of 1, 2, 6, 12, 18, and 24 hours for the surface level and levels 3 and 6. Each row of a matrix represents the starting or initial conditions, and the columns represent the change that occurred on succeeding observations. For example, if a wind speed of 10 kt changed to 20 kt after a given time lag, the occurrence would be noted in the row for initial wind speeds in the interval 10.0-14.9 kt under the column for succeeding wind speeds in the

TABLE 2. CUMULATIVE RELATIVE FREQUENCY DISTRIBUTIONS FOR WIND SPEEDS (KT).

LEVEL	HEIGHT (FT)	5.0%	50.0%	95.0%	99.0%
SURFACE	40	2.5	9.0	19.5	23.5
1	146	4.5	12.5	24.0	28.5
2	296	5.5	15.0	27.0	32.0
3	581	5.5	17.0	31.0	35.0
4	874	5.5	18.0	36.0	41.0
5	1166	6.0	19.0	40.5	46.5
6	1458	5.5	19.0	42.0	49.0

TABLE 3. CUMULATIVE RELATIVE FREQUENCY DISTRIBUTIONS FOR PEAK GUSTS (KT).

LEVEL	HEIGHT (FT)	5.0%	50.0%	95.0%	99.0%
SURFACE	40	2.0	10.5	25.5	30.5
1	146	4.0	13.0	29.0	34.5
2	296	5.0	15.5	31.0	37.0
3	581	5.0	17.5	34.0	38.5
4	874	5.0	18.5	38.0	43.0
5	1166	5.5	19.0	41.5	48.5
6	1458	5.0	19.0	42.0	49.0

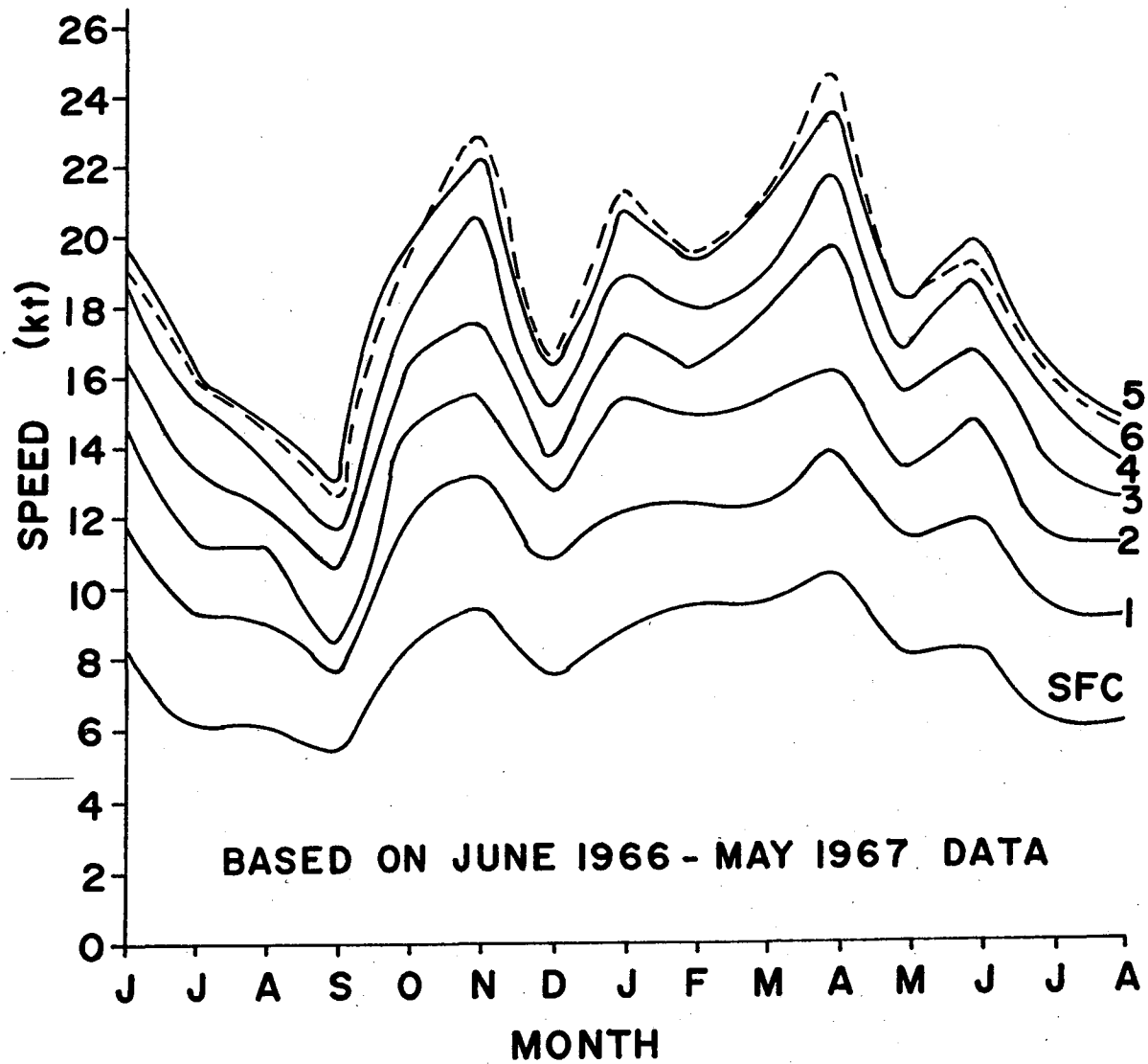


Figure 10. Monthly arithmetic mean wind speeds for the 7 levels.

interval 20.0-24.9 kt. Then, if this 20 kt wind changed to 30 kt after the same time lag, the occurrence would be noted in the row 20.0-24.9 kt under the column 30.0-34.9 kt.

Each row was then normalized by dividing each element of the row by the sum of the entries in that row. These modified contingency tables, known as transition matrices (Lipschutz, 1966), are shown in tables 4A, 4B, 5A, 5B, 6A, and 6B for time lags of 1 and 24 hours at the surface and levels 3 and 6. The rows and columns are labeled with speed values in the middle of the interval. Observation pairs containing a missing observation were not tabulated. The last entry in each row is the total number of entries in that row. For example, there were 172 cases in which the surface wind speed was zero (table 4A).

TABLE 4A. TRANSITION MATRIX FOR SPEED CHANGE FOR TIME LAG OF 1 HOUR FOR THE SURFACE LEVEL.

	CALM	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	NO.
CALM	.325	.610	.063	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	172
2.5	.042	.714	.227	.013	.000	.000	.000	.000	.000	.000	.000	.000	.000	2540
7.5	.002	.191	.667	.132	.004	.000	.000	.000	.000	.000	.000	.000	.000	3067
12.5	.000	.016	.211	.634	.130	.006	.000	.000	.000	.000	.000	.000	.000	1906
17.5	.000	.003	.021	.296	.595	.080	.002	.000	.000	.000	.000	.000	.000	842
22.5	.000	.000	.023	.047	.449	.425	.053	.000	.000	.000	.000	.000	.000	167
27.5	.000	.000	.000	.000	.142	.714	.142	.000	.000	.000	.000	.000	.000	14
32.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
37.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
42.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
47.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
52.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
57.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
ANN	.020	.292	.352	.219	.097	.019	.002	.000	.000	.000	.000	.000	.000	8727

TABLE 4B. TRANSITION MATRIX FOR SPEED CHANGE FOR TIME LAG OF 24 HOURS FOR THE SURFACE LEVEL.

	CALM	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	NO.
CALM	.052	.421	.309	.157	.046	.011	.000	.000	.000	.000	.000	.000	.000	171
2.5	.030	.400	.344	.156	.052	.013	.001	.000	.000	.000	.000	.000	.000	2530
7.5	.016	.294	.406	.193	.077	.010	.000	.000	.000	.000	.000	.000	.000	3041
12.5	.009	.180	.314	.320	.143	.029	.002	.000	.000	.000	.000	.000	.000	1904
17.5	.016	.205	.265	.272	.199	.036	.003	.000	.000	.000	.000	.000	.000	843
22.5	.023	.227	.317	.239	.131	.053	.005	.000	.000	.000	.000	.000	.000	167
27.5	.071	.142	.285	.214	.142	.071	.071	.000	.000	.000	.000	.000	.000	14
32.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
37.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
42.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
47.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
52.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
57.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
ANN	.020	.292	.352	.219	.097	.019	.002	.000	.000	.000	.000	.000	.000	8727

TABLE 5A. TRANSITION MATRIX FOR SPEED CHANGE FOR TIME LAG OF 1 HOUR FOR LEVEL 3.

	CALM	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	NO.
CALM	.396	.507	.095	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	63
2.5	.050	.585	.326	.028	.006	.003	.000	.000	.000	.000	.000	.000	.000	659
7.5	.002	.139	.584	.245	.022	.004	.000	.000	.000	.000	.000	.000	.000	1534
12.5	.000	.009	.183	.602	.184	.017	.001	.000	.000	.000	.000	.000	.000	2092
17.5	.000	.003	.016	.227	.527	.210	.012	.001	.000	.000	.000	.000	.000	1664
22.5	.000	.001	.001	.029	.225	.558	.173	.009	.000	.000	.000	.000	.000	1505
27.5	.000	.000	.000	.008	.021	.283	.570	.110	.004	.001	.000	.000	.000	898
32.5	.000	.000	.003	.011	.019	.051	.375	.486	.047	.003	.000	.000	.000	253
37.5	.000	.000	.000	.000	.035	.035	.107	.392	.357	.071	.000	.000	.000	28
42.5	.000	.000	.000	.000	.000	.000	.200	.400	.200	.200	.000	.000	.000	5
47.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
52.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
57.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
ANN	.007	.076	.176	.240	.191	.173	.103	.029	.003	.001	.000	.000	.000	8717

TABLE 5B. TRANSITION MATRIX FOR SPEED CHANGE FOR TIME LAG OF 24 HOURS FOR LEVEL 3.

	CALM	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	NO.
CALM	.000	.142	.142	.349	.126	.142	.095	.000	.000	.000	.000	.000	.000	63
2.5	.004	.143	.266	.240	.149	.102	.080	.012	.000	.000	.000	.000	.000	656
7.5	.010	.126	.268	.253	.160	.106	.057	.013	.003	.000	.000	.000	.000	1517
12.5	.007	.094	.191	.292	.191	.134	.064	.021	.001	.000	.000	.000	.000	2073
17.5	.005	.048	.142	.256	.242	.188	.085	.028	.000	.001	.000	.000	.000	1657
22.5	.010	.040	.116	.192	.214	.240	.142	.036	.006	.000	.000	.000	.000	1499
27.5	.003	.028	.109	.142	.155	.252	.236	.064	.005	.001	.000	.000	.000	898
32.5	.000	.016	.116	.264	.128	.240	.152	.072	.012	.000	.000	.000	.000	250
37.5	.000	.035	.250	.035	.178	.285	.107	.071	.035	.000	.000	.000	.000	28
42.5	.000	.000	.200	.400	.200	.000	.200	.000	.000	.000	.000	.000	.000	5
47.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
52.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
57.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	0
ANN	.007	.076	.176	.240	.191	.173	.103	.029	.003	.001	.000	.000	.000	8717

TABLE 6A. TRANSITION MATRIX FOR SPEED CHANGE FOR TIME LAG OF 1 HOUR FOR LEVEL 6.

	CALM	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	NO.
CALM	.371	.628	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	35
2.5	.028	.655	.272	.037	.005	.000	.000	.000	.000	.000	.000	.000	.000	668
7.5	.002	.141	.591	.244	.017	.002	.000	.000	.000	.000	.000	.000	.000	1294
12.5	.000	.012	.177	.586	.201	.016	.004	.000	.000	.000	.000	.000	.000	1726
17.5	.000	.001	.021	.235	.516	.197	.020	.004	.000	.002	.000	.000	.000	1395
22.5	.000	.002	.002	.027	.196	.544	.203	.019	.003	.000	.000	.000	.000	1236
27.5	.000	.000	.002	.010	.045	.240	.503	.182	.015	.000	.000	.000	.000	916
32.5	.000	.000	.000	.005	.013	.052	.228	.477	.196	.023	.001	.000	.000	590
37.5	.000	.000	.000	.000	.007	.002	.062	.226	.487	.193	.020	.000	.000	398
42.5	.000	.000	.000	.000	.010	.003	.023	.067	.209	.540	.138	.006	.000	296
47.5	.000	.000	.000	.000	.000	.007	.000	.015	.047	.330	.503	.094	.000	127
52.5	.000	.000	.000	.000	.000	.000	.000	.000	.030	.030	.363	.545	.030	33
57.5	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.500	.500	2
ANN	.004	.077	.149	.198	.160	.142	.105	.068	.046	.034	.015	.006	.000	8734

TABLE 6B. TRANSITION MATRIX FOR SPEED CHANGE FOR TIME LAG OF 24 HOURS FOR LEVEL 6.

	CALM	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	NO.
CALM	.029	.088	.088	.117	.235	.235	.000	.058	.147	.000	.000	.000	.000	34
2.5	.007	.137	.223	.244	.134	.112	.077	.025	.025	.007	.002	.000	.000	667
7.5	.009	.128	.227	.213	.156	.112	.061	.044	.019	.017	.006	.002	.000	1286
12.5	.004	.108	.169	.261	.181	.101	.067	.054	.028	.016	.003	.000	.001	1718
17.5	.002	.071	.148	.230	.191	.135	.098	.053	.026	.025	.010	.003	.000	1392
22.5	.000	.039	.116	.175	.147	.215	.144	.073	.034	.031	.012	.007	.000	1232
27.5	.004	.041	.100	.162	.162	.174	.165	.076	.042	.040	.020	.007	.000	915
32.5	.000	.028	.098	.103	.136	.142	.159	.141	.103	.052	.028	.003	.000	588
37.5	.000	.040	.068	.098	.124	.129	.139	.101	.141	.116	.037	.002	.000	395
42.5	.000	.010	.077	.084	.081	.179	.114	.138	.162	.108	.043	.000	.000	296
47.5	.000	.015	.047	.133	.039	.102	.118	.141	.125	.141	.110	.023	.000	127
52.5	.000	.000	.030	.121	.363	.181	.030	.030	.060	.030	.090	.060	.000	33
57.5	.000	.000	.000	.000	.000	.000	.500	.500	.000	.000	.000	.000	.000	2
ANN	.004	.077	.149	.198	.160	.142	.105	.068	.046	.034	.015	.006	.000	8734

Elements of a row of a transition matrix are relative frequencies or probability estimates for various speed changes that occurred to the initial speed. These elements will be referred to as probabilities. For example, at the surface level, 63.4% of the winds (a probability of 0.634) in the interval 10.0-14.9 kt remained unchanged an hour later (time lag of 1 hour). The last row in each matrix is the annual relative frequency distribution of wind speeds in the same intervals as the matrices. The last entry in this row represents the total number of observations at each of the levels during the year. For example, there were 8727 wind speed observations and 33 missing observations at the surface level (table 4A and 4B) during the year.

Surface wind speeds are most likely to remain constant (no change in speed category) for speeds up to 20 kt for 1 and 2 hour time lags. For longer time lags the surface speeds generally remain steady below 15 kt and decrease with time for speeds above 15 kt. This does not mean that a 25 kt wind will decrease to 10-15 kt within a day, but that there is, for example, a 0.214 probability for a 10 kt wind 24 hours after observing a 25 kt wind and only a 0.071 probability of its remaining at 25 kt 24 hours later (table 4B). The best estimate of surface wind speeds a day later is contained in the interval 5.0-9.9 kt. For most speed categories, speeds have a 30 to 40% chance of being in this interval at the end of 24 hours. This is consistent with the fact that the mean surface speed for the 1 year sample is 8.1 kt. Calm surface winds are most likely to be in the interval 0.1-4.9 kt on any future observation.

Wind speeds at levels 3 and 6 tend to remain unchanged for a 1 hour time lag. For example, a wind speed in the interval 45.0-49.9 kt at level 6 has a 0.503 probability (65 of the 127 cases) of being in that interval 1 hour later. When the time lag is 24 hours, winds at levels 3 and 6 generally increase with time below 5 kt, remain steady between 5 and 25 kt, and decrease above 25 kt. The patterns shift fairly smoothly with time from those at a 1 hour time lag to those at a 24 hour time lag.

5.4 Change of Wind Speed with Height

Changes of wind speed with height between the surface and level 3 and between the surface and level 6 were examined in the manner used to study the change of wind speed with time (sec. 5.3). The same speed classes were used in both instances. The transition matrices are shown in tables 7A and 7B.

For most of the surface speed classes, the wind is most likely to increase to the next higher speed class in both tables. The wind speed seldom decreases with height. For a given surface speed class, the probability for strong winds is greater at level 6 than at level 3. For example, for the surface speed class 20.0-24.9 kt, 1.9% of the winds at level 3 and 10.6% of the winds at level 6 were in the interval 40.0-44.9 kt. This is also shown in the cumulative relative frequencies (tables 8A and 8B), which were determined from data in tables 7A and 7B. Values are rounded to the nearest 0.5 kt. If the surface wind speed is in the interval 20.0-24.9 kt,

TABLE 7A. TRANSITION MATRIX FOR WIND SPEED CHANGE (KT) BETWEEN THE SURFACE LEVEL AND LEVEL 3.

LEV 3 SFC	CALM	0.1- 4.9	5.0- 9.9	10.0- 14.9	15.0- 19.9	20.0- 24.9	25.0- 29.9	30.0- 34.9	35.0- 39.9	40.0- 44.9	45.0- 49.9	50.0- 54.9	55.0- 59.9	NO.
CALM	.081	.382	.306	.185	.040	.006	.000	.000	.000	.000	.000	.000	.000	173
0.1- 4.9	.019	.199	.250	.272	.176	.073	.012	.000	.000	.000	.000	.000	.000	2539
5.0- 9.9	.001	.030	.260	.279	.201	.167	.060	.003	.000	.000	.000	.000	.000	3066
10.0-14.9	.000	.000	.026	.262	.260	.245	.175	.031	.001	.000	.000	.000	.000	1887
15.0-19.9	.000	.000	.000	.021	.121	.371	.321	.157	.006	.001	.000	.000	.000	840
20.0-24.9	.000	.000	.000	.000	.019	.173	.420	.265	.105	.019	.000	.000	.000	162
25.0-29.9	.000	.000	.000	.000	.000	.077	.154	.462	.231	.077	.000	.000	.000	13

TABLE 7B. TRANSITION MATRIX FOR WIND SPEED CHANGE (KT) BETWEEN THE SURFACE LEVEL AND LEVEL 6.

LEV 6 SFC	CALM	0.1- 4.9	5.0- 9.9	10.0- 14.9	15.0- 19.9	20.0- 24.9	25.0- 29.9	30.0- 34.9	35.0- 39.9	40.0- 44.9	45.0- 49.9	50.0- 54.9	55.0- 59.9	NO.
CALM	.052	.295	.358	.231	.040	.017	.000	.006	.000	.000	.000	.000	.000	173
0.1- 4.9	.009	.193	.227	.234	.171	.108	.046	.009	.002	.001	.000	.000	.000	2540
5.0- 9.9	.001	.041	.199	.242	.145	.147	.122	.072	.021	.009	.001	.000	.000	3061
10.0-14.9	.000	.002	.024	.177	.226	.150	.101	.109	.112	.072	.027	.002	.000	1918
15.0-19.9	.000	.001	.001	.014	.085	.235	.221	.115	.098	.126	.077	.026	.001	847
20.0-24.9	.000	.000	.000	.000	.025	.113	.275	.231	.150	.106	.044	.050	.006	160
25.0-29.9	.000	.000	.000	.000	.000	.154	.000	.154	.462	.231	.000	.000	.000	13

TABLE 8A. CUMULATIVE RELATIVE FREQUENCY DISTRIBUTIONS FOR WIND SPEED CHANGE (KT) BETWEEN THE SURFACE LEVEL AND LEVEL 3.

SFC. SPEED	10 %	50 %	90 %	99 %
CALM	0	5.0	13.0	19.0
.1- 4.9	2.5	10.0	19.5	25.0
5.0- 9.9	7.0	13.5	23.5	28.0
10.0-14.9	12.0	19.0	27.5	31.5
15.0-19.9	19.0	24.5	31.0	34.5
20.0-24.9	23.0	28.5	35.5	41.0
25.0-29.9	26.0	33.0	39.0	43.0

TABLE 8B. CUMULATIVE RELATIVE FREQUENCY DISTRIBUTIONS FOR WIND SPEED CHANGE (KT) BETWEEN THE SURFACE LEVEL AND LEVEL 6.

SFC. SPEED	10 %	50 %	90 %	99 %
CALM	6.0	12.0	19.0	28.0
.1- 4.9	3.0	11.5	22.5	30.5
5.0- 9.9	7.0	15.5	30.0	40.0
10.0-14.9	13.0	22.5	40.0	47.0
15.0-19.9	20.0	28.5	46.5	51.5
20.0-24.9	24.0	32.0	45.0	54.0
25.0-29.9	24.0	37.0	41.5	43.0

10% of the wind speeds at the third level were not greater than 23.0 kt, 50% were not greater than 28.5 kt, 90% were not greater than 35.5 kt, and 99% were not greater than 41.0 kt, while at the sixth level 10% were not greater than 24.0 kt, 50% were not greater than 32.0 kt, 90% were not greater than 45.0 kt, and 99% were not greater than 54.0 kt.

5.5 Diurnal Variations

It has been shown how the wind speeds change with height (tables 7A and 7B) and from month to month (table 1 and fig. 10). The change of the mean wind speed on a diurnal basis for the year was determined (fig. 11) using

$$V_{yh} = \frac{1}{12} \sum_{m=1}^{12} \left(\frac{1}{n_d} \sum_{d=1}^{n_d} V_h\right) , \qquad (6)$$

where V_{yh} is the annual mean speed at hour h for a given tower level. The quantity in parentheses is the monthly mean speed for the same hour and level as V_{yh}. The extremes of sunrise and sunset during the year are plotted in figure 11. Speed profiles for 0000, 0600, 1200, and 1800 CST are shown in figure 12.

Mean wind speeds generally increase with height and reach a maximum at level 6. An exception to this occurs between 1100 and 1500 CST when the speeds at level 2 are higher than those at level 3. This is shown clearly in figure 12 by the 1200 CST profile. A more detailed investigation of this phenomena indicated that this inflection in the wind profile was a real event and was not just the result of a faulty instrument at either level 2, 3, or 4. However, an explanation of this phenomenon is beyond the scope of this report and is not possible until a detailed analysis of the temperature data can be made.

Surface wind speeds are at a minimum during nighttime hours, increasing from sunrise to a maximum of 10.3 kt between 1300 and 1500 CST. The surface speed begins to decrease just before sunset and reaches its lowest value of the day (6.4 kt) around 2000 CST. The mean surface speeds increase slightly after this time, remaining near 7 kt until sunrise.

At the upper levels, winds are higher at night than during the day. They reach a maximum of about 23 kt at levels 5 and 6 around 0000-0100 CST and decrease quite rapidly after sunrise to a minimum of 13.7 kt around 1200-1300 CST. There is a 1-2 hour lag between the time of the upper level minimum and the surface level maximum. Most of the speed change occurs in a short time period after sunrise between 0800-1000 CST during which time the upper level winds decrease by almost 40% from the nighttime maximums. The speed changes that occur around sunrise indicate that the profiles are influenced by momentum transfer due to the convective mixing during the daylight hours. For instance, surface speeds begin to increase between 0500 and 0600 CST while the upper level winds begin their marked decrease around 0700 CST. Thus, there is a 1-2 hour lag between the time of

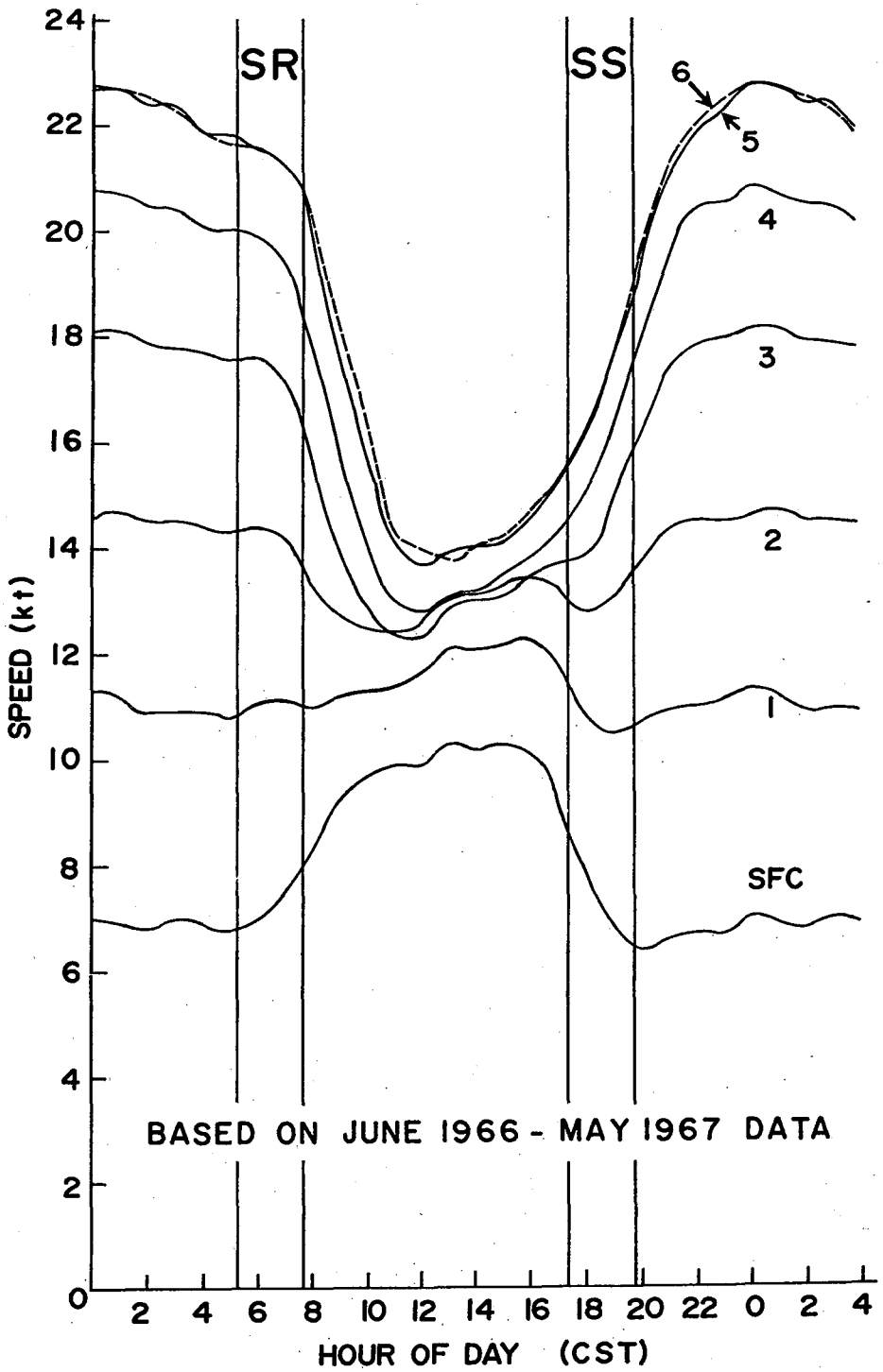


Figure 11. Diurnal variations of mean wind speeds on an annual basis.

A striking feature shown by this figure is the large amount of change in the gust factor occurring during midmorning and late afternoon with an associated maximum in between. This sharp increase in gust factor generally occurs during the 2-hour period between 0800 and 1000 CST and the corresponding decrease occurring between 1600 and 1800 CST. This 2-hour period of increasing gust factors corresponds to the period of marked decrease in the mean wind speed at the upper levels (fig. 11). Gust factors increase by about 25% while the upper level winds decrease by as much as 40%. The period of maximum gust factors, occurring between 1100 and 1500 CST, is also the period of minimum upper level winds. Thus, as Davis and Newstein found, the gust factors decrease with increasing speeds.

There were no significant differences between the annual plot of the diurnal variation of the gust factors and the individual monthly plots. Such features as the maximum and minimum values of the gust factor for each hour and each level, the times of the midmorning and late afternoon changes, and the height of the midday maximum in the gust factors are well approximated by the data in figure 14.

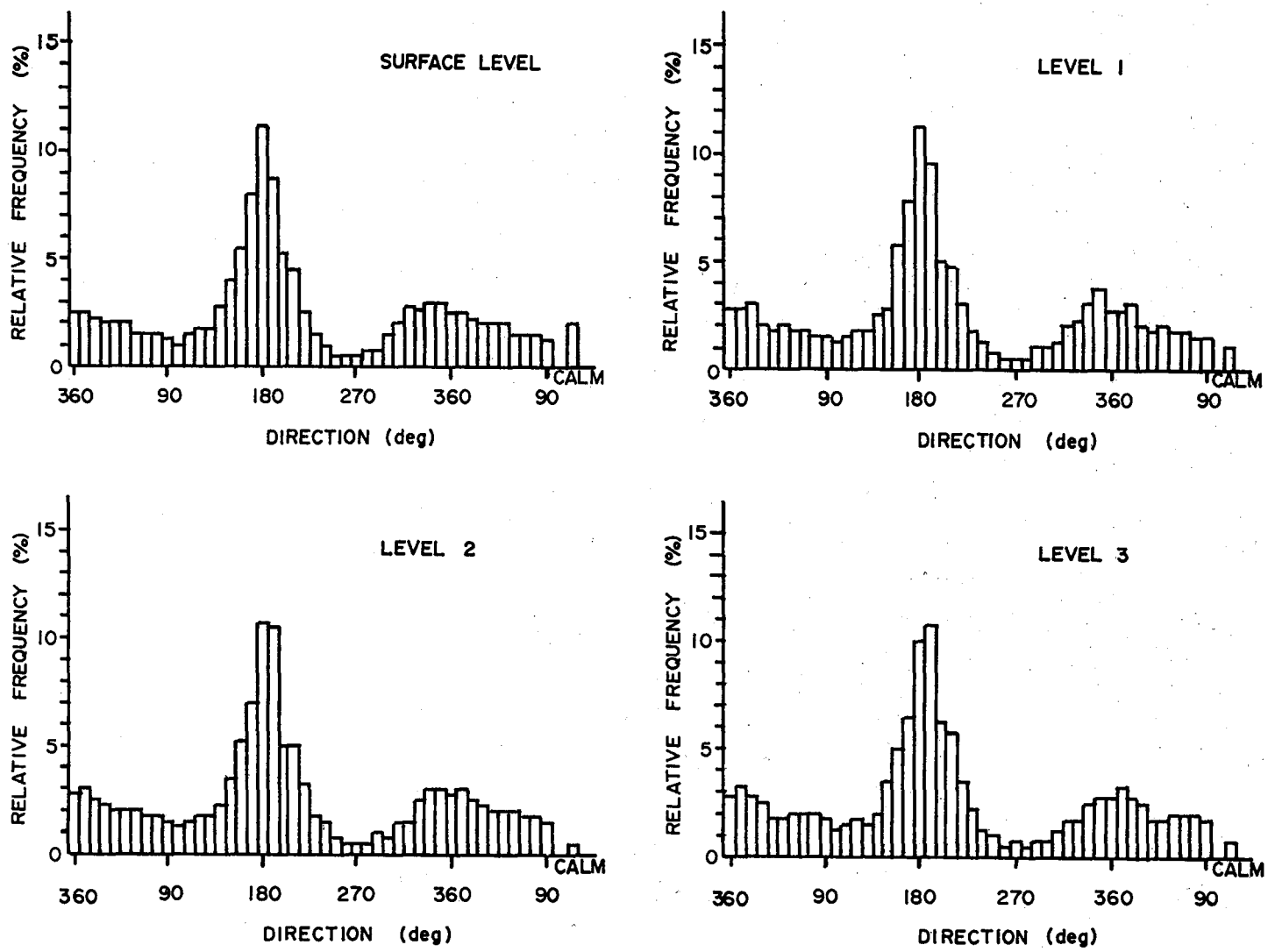
6. CHARACTERISTICS OF THE WIND DIRECTION

6.1 Monthly and Annual Relative Frequency Distributions

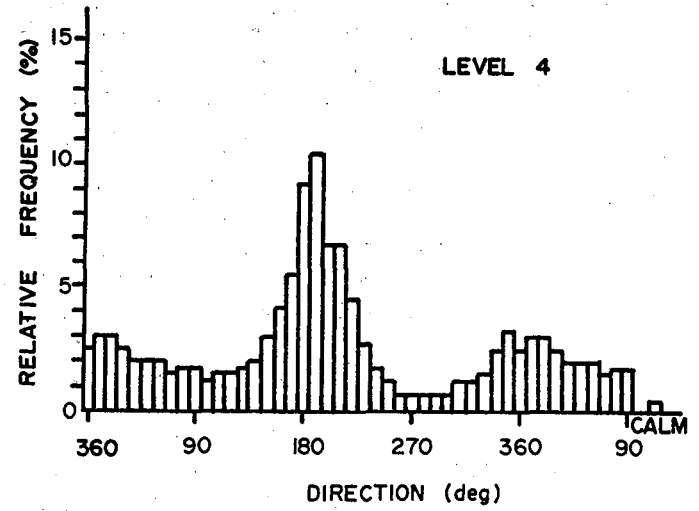
The annual frequency distributions of wind direction (fig. 15A-G) in 10° intervals (5°-14°, 15°-24°, 25°-34°, etc.) are bimodal with most of the winds being either southerly or northerly. The primary peak occurs in the 10° sector centered at 180° at the surface and levels 1 and 2 and at 190° at the higher levels. The secondary (northerly) peak has less than 3.5% of the total observations in any 10° sector and varies from 340° through north to 20°. These data were also grouped in four quadrants centered on 0°, 90°, 180°, and 270°. The average annual distribution for the tower layer, the layer between the surface level and the top level, shows that approximately 53% of the winds were from the south, 22% from the north, 14% from the east, 10% from the west, and 1% were calm. Percentages at individual levels differ from the above values by less than 3%.

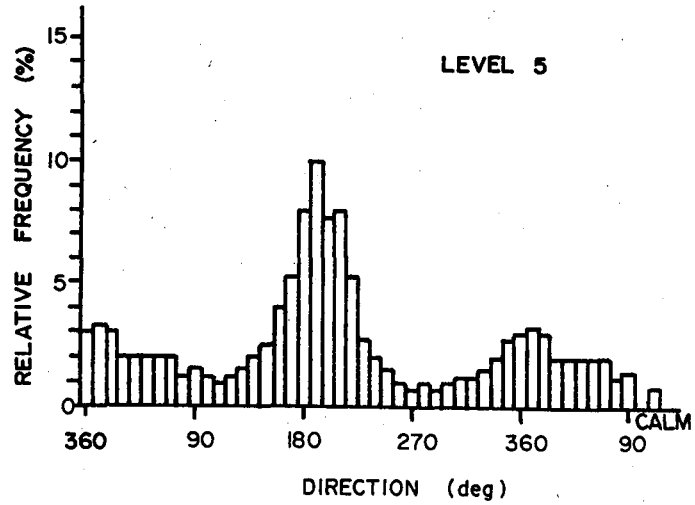
The annual frequency distributions of wind direction (fig. 15A-G) indicate that most winds are either southerly or northerly in Oklahoma. Northerly winds in Oklahoma are almost always associated with cold frontal passages. Since cold frontal passages are frequent in winter and rare in summer, it was expected that southerly winds would dominate year round and that northerly winds would be far more frequent in winter than in summer. The monthly frequency distributions of wind direction in 10° intervals and by quadrant for the surface level (fig. 16A-L) show this trend in general but also show considerable month to month variability.

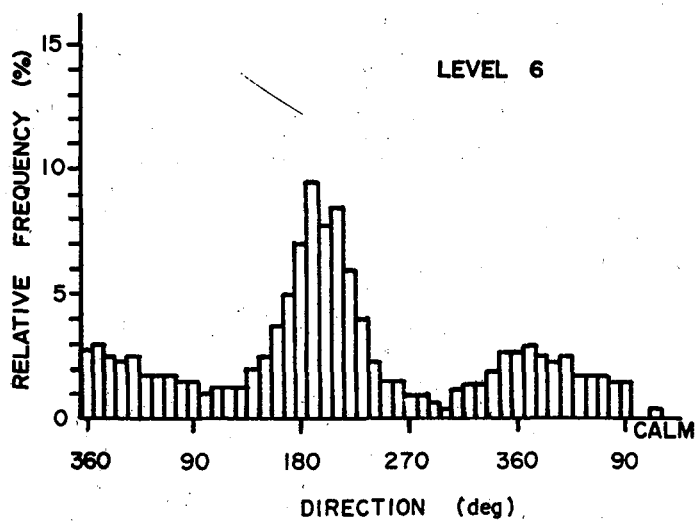
Southerly winds were dominant in June and July 1966. Northerly winds became more frequent during the next 2 months with September having nearly as many northerly as southerly winds. September had the lowest frequency of southerly winds. October and November were dominated by southerly winds and thus deviated from the expected pattern.



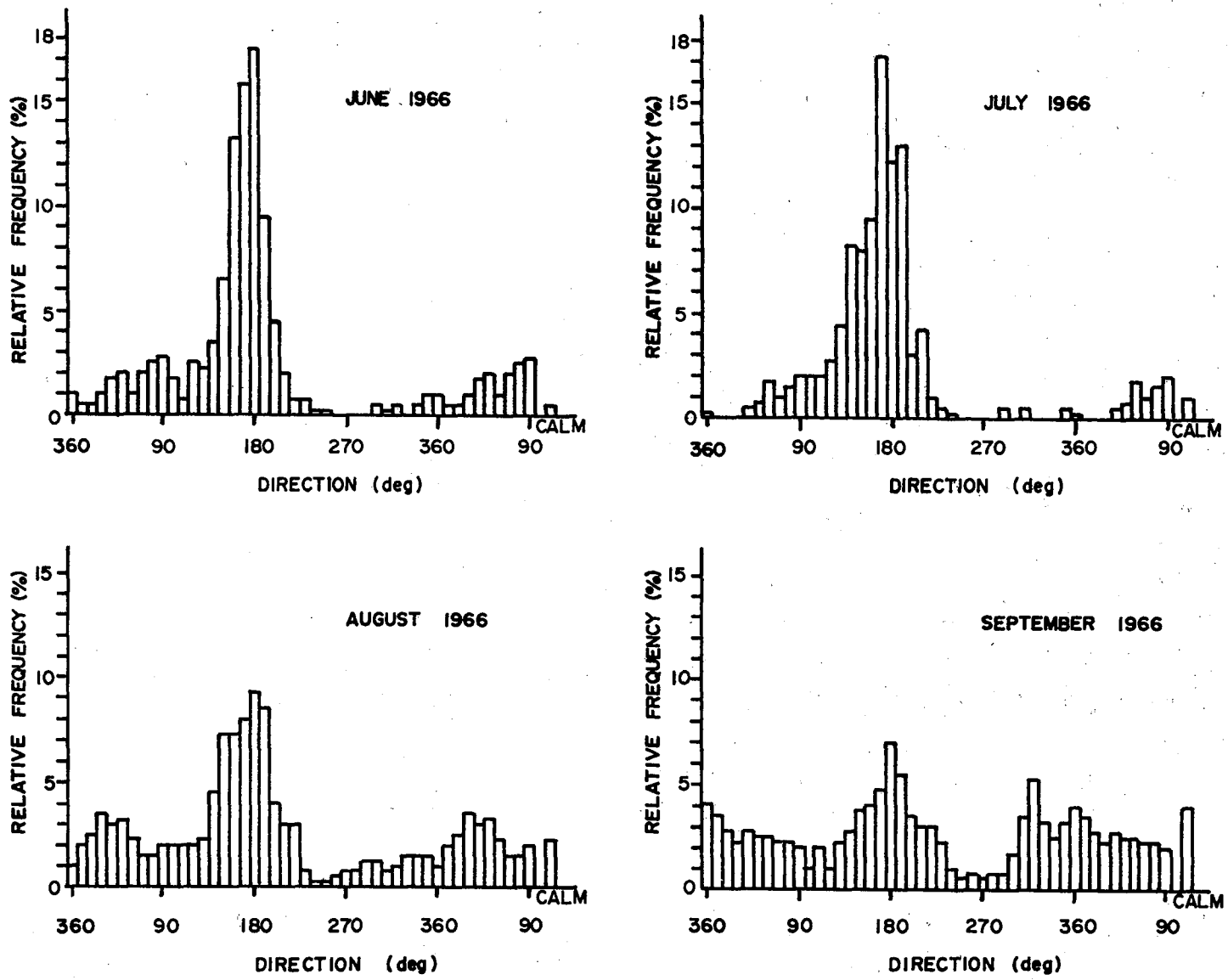
Figures 15A-D. Annual relative frequency distributions of wind direction for A) surface level, B) level 1, C) level 2, and D) level 3.



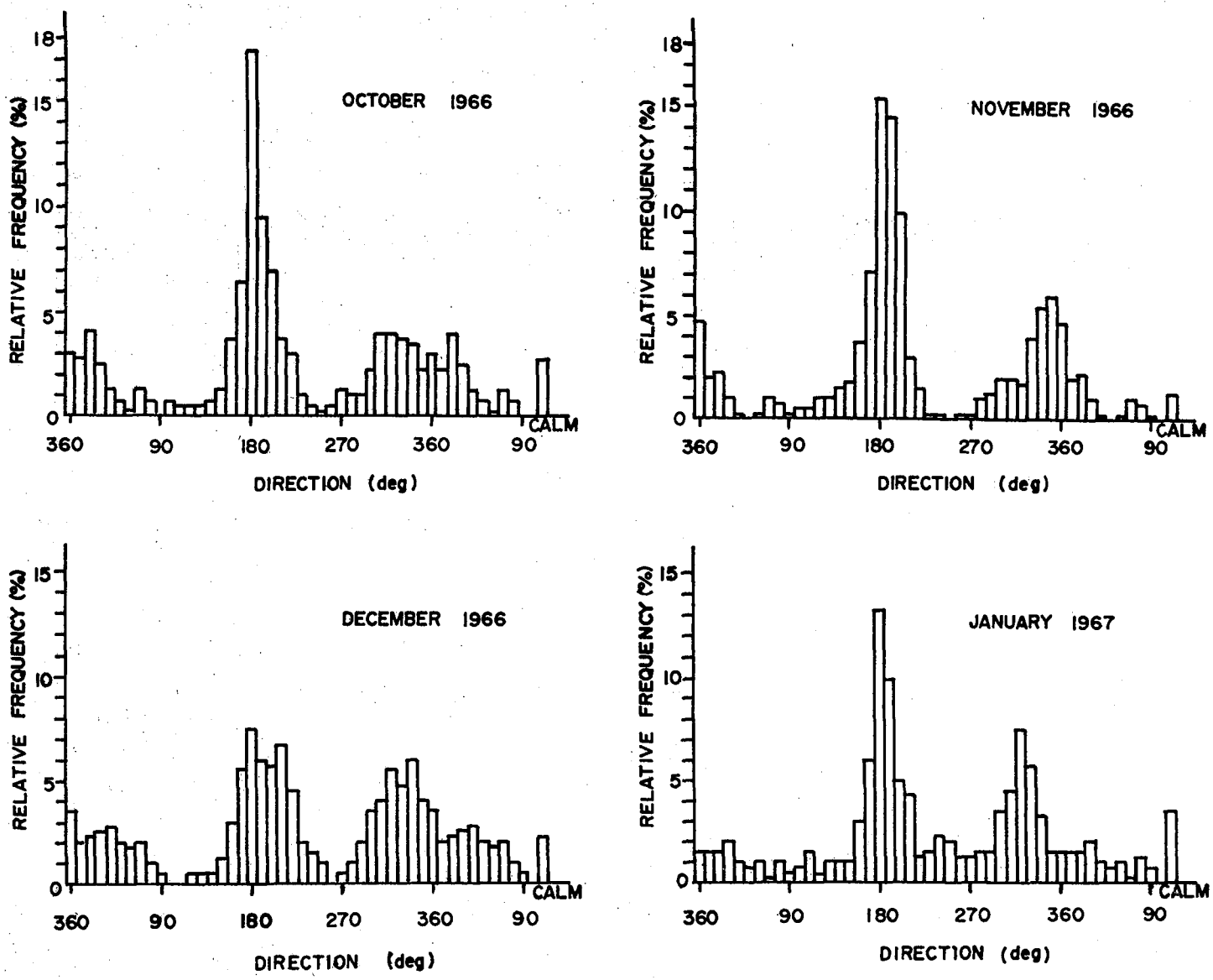




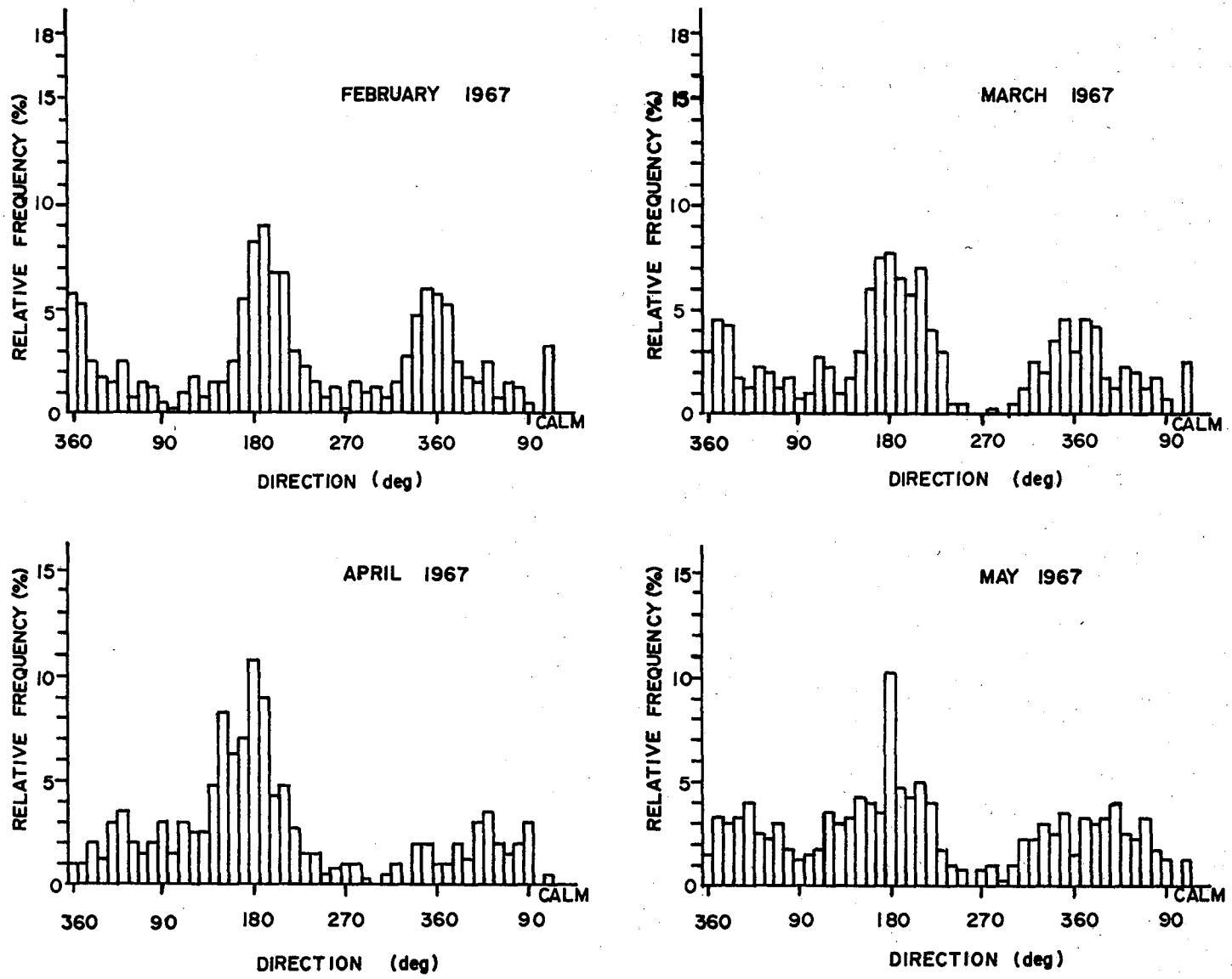
Figures 15E-G. Annual relative frequency distributions of wind direction for E) level 4, F) level 5, and G) level 6.



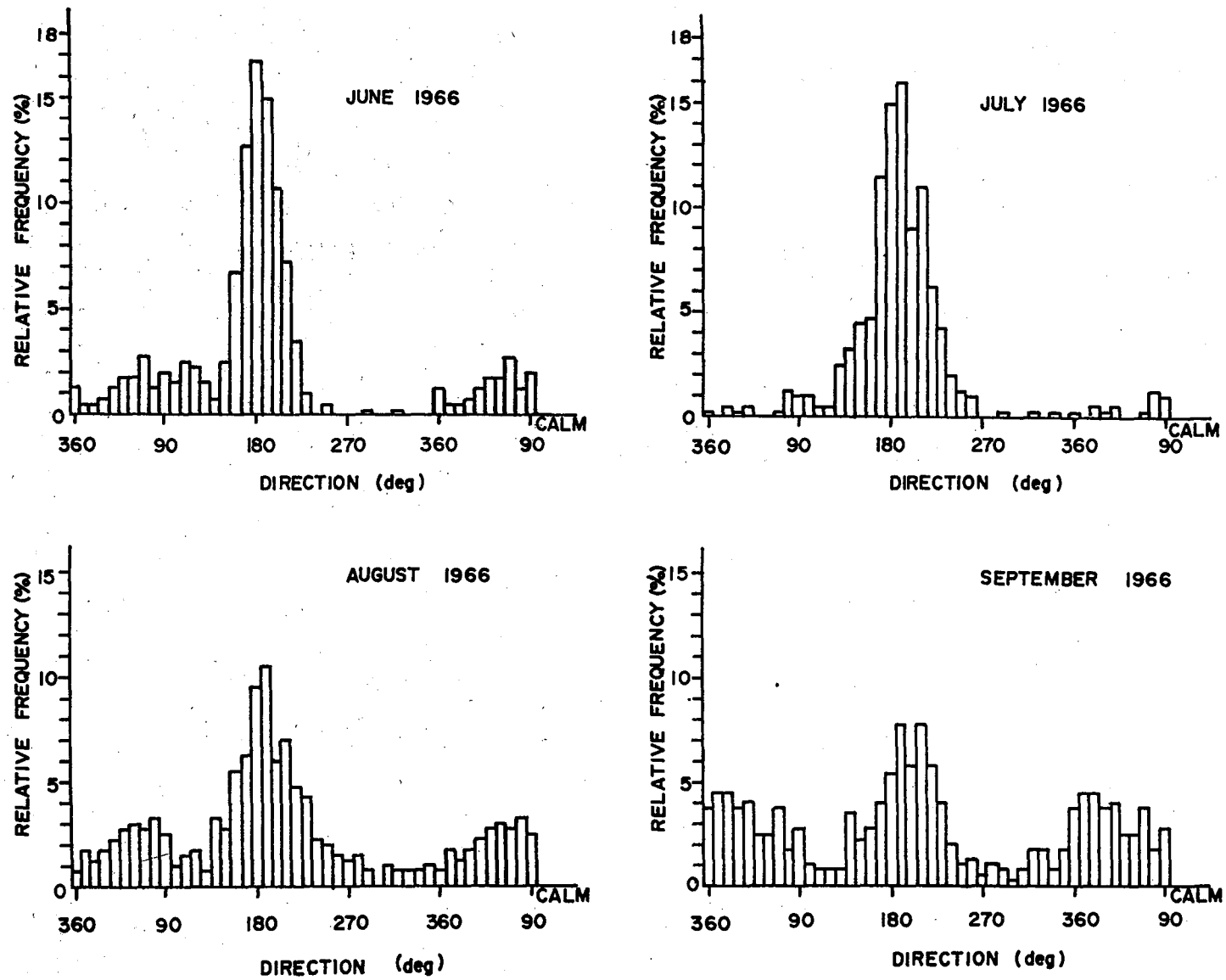
Figures 16A-D. Monthly relative frequency distributions of wind direction for the surface level for A) June 1966 (6.7% N, 17.4% E, 73.1% S, 2.4% W, 0.4% calm), B) July 1966 (1.6% N, 18.5% E, 76.9% S, 2.0% W, 1.0% calm), C) August 1966 (17.8% N, 18.5% E, 54.9% S, 6.5% W, 2.3% calm), and D) September 1966 (29.6% N, 17.9% E, 37.0% S, 11.6% W, 3.9% calm).



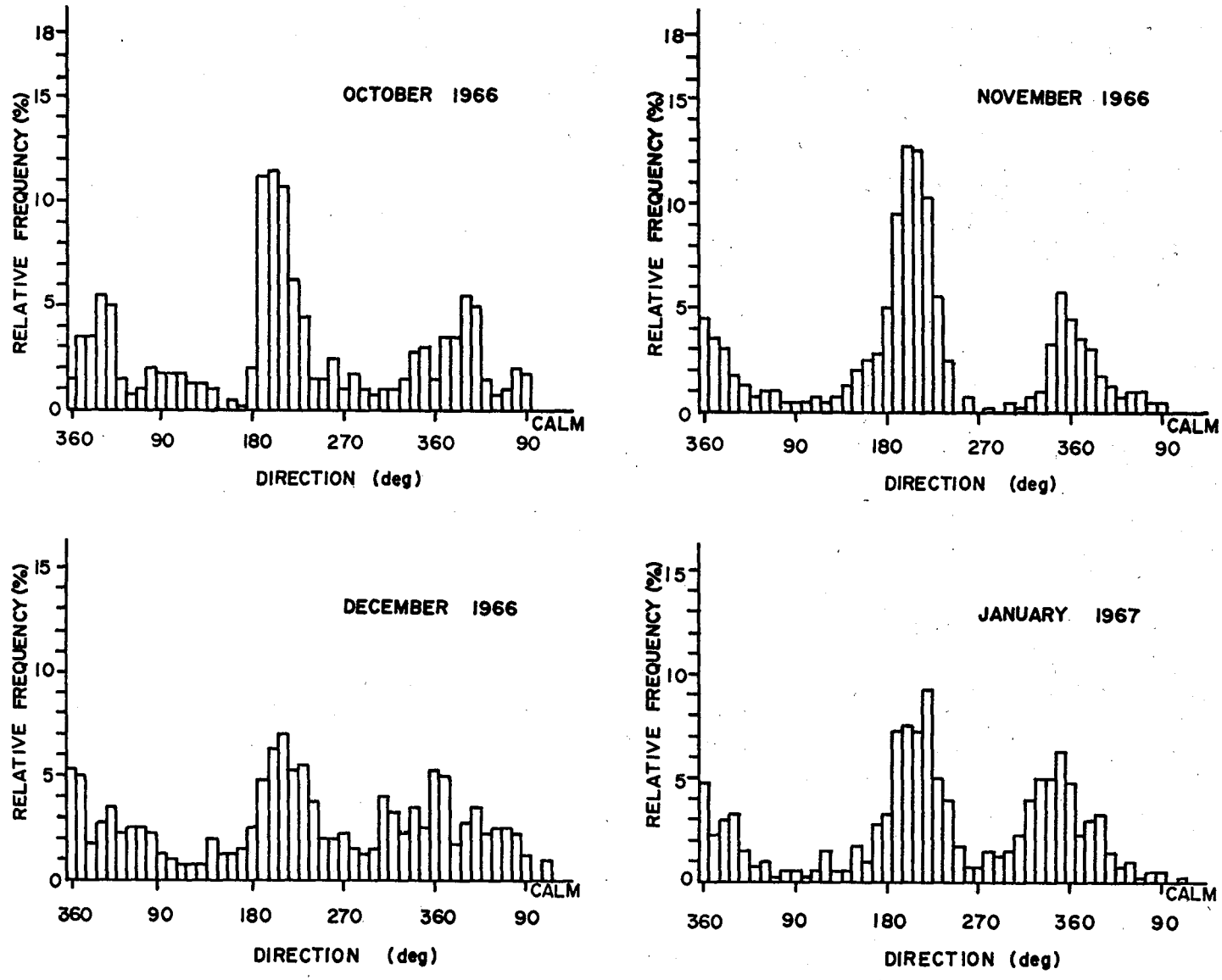
Figures 16E-H. Monthly relative frequency distributions of wind direction for the surface level for E) October 1966 (27.1% N, 5.5% E, 53.1% S, 11.5% W, 2.8% calm), F) November 1966 (27.7% N, 5.2% E, 58.7% S, 7.2% W, 1.2% calm), G) December 1966 (33.5% N, 8.2% E, 41.1% S, 15.0% W, 2.2% calm), and H) January 1967 (26.0% N, 7.5% E, 44.3% S, 18.8% W, 3.4% calm).



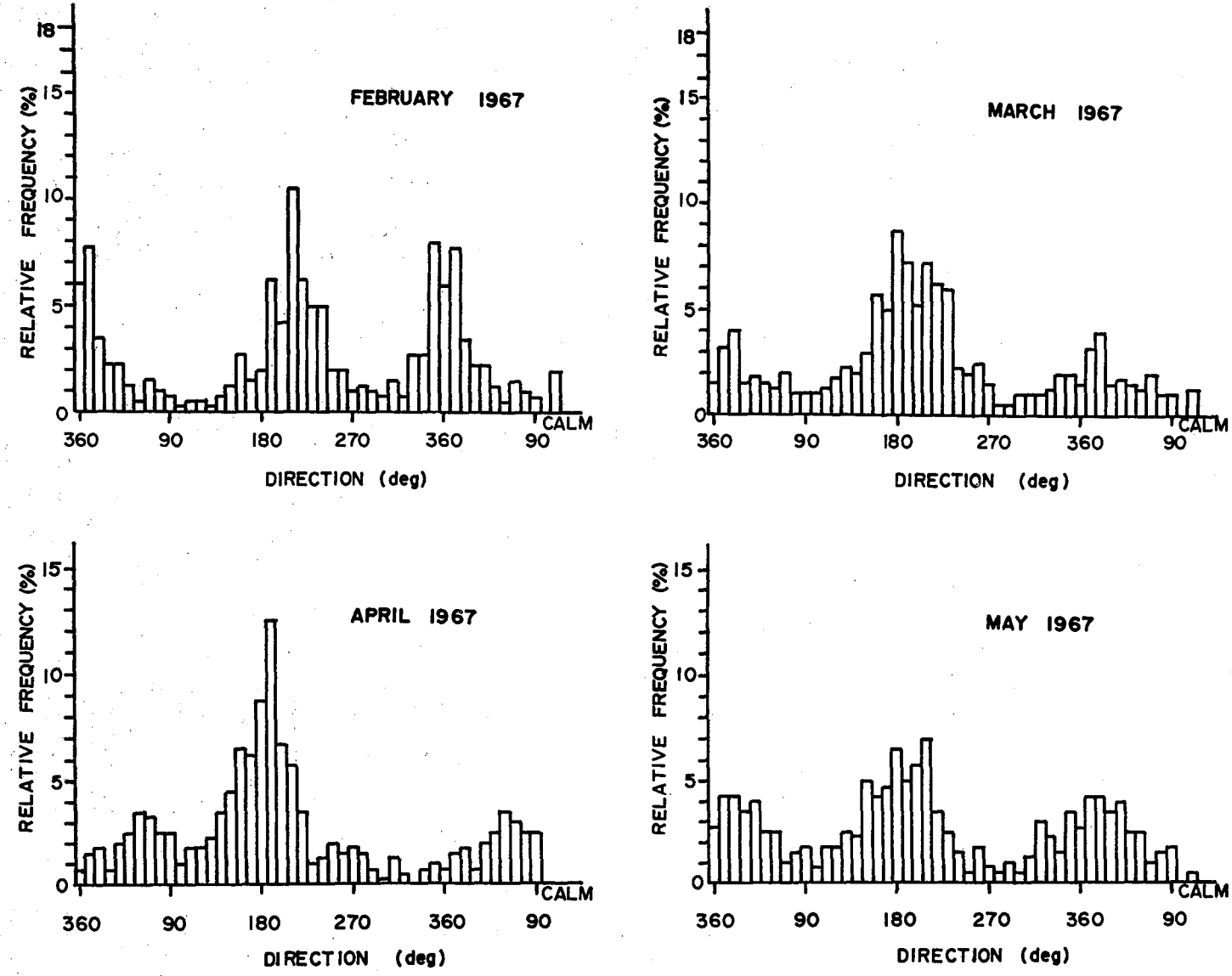
Figures 16I-L. Monthly relative frequency distributions of wind direction for the surface level for I) February 1967 (31.6% N, 10.2% E, 45.0% S, 10.0% W, 3.2% calm), J) March 1967 (27.1% N, 15.5% E, 48.8% S, 6.2% W, 2.4% calm), K) April 1967 (13.5% N, 21.4% E, 57.5% S, 7.0% W, 0.6% calm), and L) May 1967 (26.2% N, 20.1% E, 43.3% S, 9.1% W, 1.3% calm).



Figures 17A-D. Monthly relative frequency distributions of wind direction for level 6 for A) June 1966 (4.7% N, 17.4% E, 76.0% S, 1.9% W, 0.0% calm), B) July 1966 (2.0% N, 7.2% E, 81.3% S, 9.4% W, 0.1% calm), C) August 1966 (10.9% N, 19.1% E, 55.6% S, 14.4% W, 0.0% calm), and D) September 1966 (26.4% N, 16.7% E, 45.0% S, 11.9% W, and 0.0% calm).



Figures 17E-H. Monthly relative frequency distributions of wind direction for level 6 for E) October 1966 (27.5% N, 13.2% E, 43.6% S, 15.6% W, 0.1% calm), F) November 1966 (24.6% N, 6.3% E, 58.6% S, 10.4% W, 0.1% calm), G) December 1966 (29.2% N, 13.9% E, 31.7% S, 24.3% W, 0.9% calm), and H) January 1967 (34.8% N, 5.8% E, 40.6% S, 18.6% W, 0.2% calm).



Figures 17I-L. Monthly relative frequency distributions of wind direction for level 6 for I) February 1967 (35.9% N, 6.8% E, 35.9% S, 19.6% W, 1.8% calm), J) March 1967 (18.0% N, 12.9% E, 51.1% S, 16.8% W, 1.2% calm), K) April 1967 (9.0% N, 21.3% E, 58.3% S, 11.4% W, 0.0% calm), and L) May 1967 (29.2% N, 16.2% E, 43.9% S, 10.3% W, 0.4% calm).

December returned to a more even distribution. The percentage of easterly and southerly winds increased steadily from December 1966 to April 1967. May 1967 showed a decrease in winds from these two quadrants and was markedly different from June of the previous year.

The same patterns exist at level 6 (fig. 17A-L) with a shift of about 10°-20° clockwise with respect to the distribution at the surface. This shift corresponds to that discussed above for the annual distributions.

In summary, winds were most frequently in the southern quadrant every month at the surface level and every month except February 1967 at the top level when there were an equal number of north and south winds. North and west winds were more frequent in the winter half of the year (Oct.-March) than in the summer half (April-Sept.); south and east winds were more frequent in the summer half of the year than in the winter half.

6.2 Change of Wind Direction with Time

The change of wind direction with time was examined in a manner similar to that used in studying the change of wind speed with time (sec. 5.3). Thirteen categories of wind direction (calm, 345°-14°, 15°-44°, ..., 315°-344°) were used. Transition matrices were calculated for time lags of 1, 2, 6, 12, 18, and 24 hours for the surface and levels 3 and 6 (i.e., for the same time lags and levels used in sec. 5.3). Matrices for 1 and 24 hour time lags for these three levels are shown in tables 10A, 10B, 11A, 11B, 12A, and 12B. For example, 74.2% of the southerly winds (165°-194° sector) at the surface remained unchanged an hour later (time lag of 1 hour) and only 0.4% became westerly (255°-284°). The last row in each matrix is the annual relative frequency distribution of wind direction in the same intervals as the matrices. The last entry in this row represents the total number of observations at each of the levels during the year. For example, there were 8487 wind direction observations and 273 missing observations at the surface level (table 10A and 10B) during the year.

Wind direction tends to remain constant for time intervals up to 6 hours at all levels (i.e., the highest probabilities are on the main diagonal). If a change in direction occurs, for most categories, surface winds are more likely to veer than to back for time lags up to 6 hours (i.e., the two highest probabilities are on or to the right of the main diagonal). Surface winds from 0°, 30°, 210°, and 240° sectors generally back with time. At levels 3 and 6 the two largest probabilities in each row lie on or just to the right of the main diagonal for all directions, except those in the 240° and 270° sectors, for time lags up to 6 hours. In comparing tables 10A, 11A, and 12A, it can be seen in the 1 hour matrix that the maximum probabilities in each row are about 0.10 higher at the upper levels than at the surface.

Southerly (180° sector) winds are most likely to be southerly for time lags up to 24 hours. Probability estimates range from 0.742 for a southerly wind to be southerly 1 hour later to 0.409 for it to be southerly 24 hours later. Calm surface winds tend to remain so for 1 and 2 hours but after that are likely to be replaced by a wind with a southerly component so that over 30% of calm winds become southerly (from the 30° sector centered on

TABLE 10A. TRANSITION MATRIX FOR DIRECTION CHANGE FOR TIME LAG OF 1 HOUR FOR THE SURFACE LEVEL.

	CALM	0	30	60	90	120	150	180	210	240	270	300	330	NO.
CALM	.341	.042	.030	.048	.042	.073	.091	.073	.109	.024	.012	.054	.054	164
0	.012	.584	.163	.018	.013	.007	.000	.006	.001	.003	.000	.015	.174	659
30	.015	.152	.571	.187	.027	.007	.003	.001	.000	.001	.003	.003	.023	518
60	.016	.026	.153	.508	.208	.033	.016	.007	.002	.002	.002	.002	.021	423
90	.021	.012	.024	.184	.387	.246	.067	.024	.003	.012	.000	.009	.006	325
120	.014	.004	.004	.047	.121	.440	.278	.061	.004	.004	.002	.000	.014	420
150	.013	.003	.000	.001	.014	.085	.567	.281	.015	.007	.002	.001	.003	1050
180	.007	.002	.001	.000	.003	.005	.108	.742	.109	.008	.004	.003	.002	2380
210	.012	.001	.002	.000	.000	.006	.015	.210	.629	.085	.014	.008	.011	1050
240	.020	.012	.008	.004	.012	.016	.016	.078	.297	.326	.111	.057	.037	242
270	.034	.040	.006	.000	.000	.020	.006	.040	.068	.095	.278	.292	.115	147
300	.016	.036	.005	.002	.011	.000	.013	.022	.008	.036	.088	.483	.275	360
330	.021	.200	.031	.005	.005	.004	.004	.005	.002	.005	.022	.115	.573	699
ANN	.020	.078	.061	.050	.039	.050	.124	.280	.123	.029	.018	.042	.083	8487

TABLE 10B. TRANSITION MATRIX FOR DIRECTION CHANGE FOR TIME LAG OF 24 HOURS FOR THE SURFACE LEVEL.

	CALM	0	30	60	90	120	150	180	210	240	270	300	330	NO.
CALM	.055	.061	.036	.079	.036	.055	.085	.312	.134	.018	.012	.030	.079	163
0	.034	.150	.102	.068	.044	.063	.063	.125	.091	.030	.025	.056	.143	632
30	.037	.108	.121	.115	.075	.094	.110	.096	.077	.027	.020	.033	.081	478
60	.007	.070	.065	.089	.113	.142	.208	.106	.055	.019	.002	.043	.075	413
90	.018	.057	.048	.045	.069	.103	.261	.215	.066	.009	.018	.033	.051	329
120	.036	.038	.028	.033	.036	.120	.255	.301	.043	.028	.007	.021	.048	415
150	.010	.048	.029	.033	.033	.063	.257	.375	.069	.009	.010	.012	.045	1022
180	.009	.070	.059	.031	.025	.020	.097	.409	.127	.026	.019	.029	.073	2340
210	.016	.078	.058	.072	.025	.009	.042	.281	.220	.043	.016	.042	.090	1011
240	.016	.054	.070	.058	.037	.029	.066	.212	.208	.070	.020	.050	.104	240
270	.006	.093	.046	.073	.066	.020	.066	.186	.140	.040	.020	.093	.146	150
300	.039	.094	.050	.019	.027	.050	.075	.206	.187	.036	.030	.103	.078	358
330	.034	.099	.076	.047	.036	.044	.070	.149	.151	.041	.023	.103	.121	694
ANN	.020	.078	.061	.050	.039	.050	.124	.280	.123	.029	.018	.042	.083	8487

TABLE 11A. TRANSITION MATRIX FOR DIRECTION CHANGE FOR TIME LAG OF 1 HOUR FOR LEVEL 3.

	CALM	0	30	60	90	120	150	180	210	240	270	300	330	NO.
CALM	.396	.063	.000	.031	.047	.095	.031	.095	.063	.015	.079	.031	.047	63
0	.007	.687	.167	.009	.003	.001	.001	.001	.000	.000	.000	.011	.107	769
30	.001	.147	.638	.175	.016	.004	.001	.000	.000	.000	.003	.000	.009	603
60	.004	.008	.115	.639	.194	.030	.000	.000	.000	.002	.002	.002	.002	494
90	.007	.011	.014	.109	.600	.200	.030	.007	.009	.002	.000	.002	.004	428
120	.014	.002	.004	.007	.099	.584	.251	.028	.000	.002	.002	.000	.002	421
150	.002	.004	.002	.002	.006	.062	.657	.246	.007	.004	.002	.001	.001	917
180	.001	.001	.000	.000	.002	.001	.069	.790	.119	.009	.002	.001	.000	2356
210	.001	.003	.002	.000	.002	.000	.015	.169	.693	.091	.011	.002	.004	1343
240	.002	.002	.004	.009	.002	.002	.007	.024	.242	.504	.117	.044	.034	408
270	.012	.006	.006	.006	.000	.012	.006	.012	.057	.210	.331	.242	.095	157
300	.013	.026	.022	.013	.000	.000	.008	.013	.022	.058	.094	.457	.269	223
330	.011	.225	.019	.001	.003	.001	.000	.007	.003	.005	.007	.084	.626	520
ANN	.007	.087	.069	.057	.049	.048	.107	.272	.154	.047	.018	.026	.059	8698

TABLE 11B. TRANSITION MATRIX FOR DIRECTION CHANGE FOR TIME LAG OF 24 HOURS FOR LEVEL 3.

	CALM	0	30	60	90	120	150	180	210	240	270	300	330	NO.
CALM	.000	.174	.047	.031	.015	.047	.142	.126	.206	.079	.031	.000	.095	63
0	.023	.152	.090	.082	.054	.064	.061	.130	.120	.058	.023	.041	.095	765
30	.011	.122	.130	.102	.109	.092	.079	.129	.105	.046	.016	.014	.038	604
60	.018	.070	.099	.101	.075	.111	.186	.109	.103	.038	.016	.036	.032	493
90	.004	.063	.035	.025	.070	.107	.230	.201	.089	.061	.014	.049	.046	426
120	.009	.040	.019	.028	.035	.124	.257	.267	.078	.042	.014	.028	.052	419
150	.002	.053	.037	.025	.054	.049	.250	.380	.078	.019	.007	.011	.029	904
180	.004	.071	.075	.032	.023	.016	.076	.420	.158	.030	.018	.020	.051	2330
210	.003	.077	.054	.079	.039	.016	.036	.266	.266	.059	.015	.023	.059	1339
240	.007	.083	.071	.064	.061	.032	.032	.167	.269	.081	.034	.029	.064	405
270	.000	.127	.095	.082	.070	.006	.025	.133	.197	.089	.025	.038	.108	157
300	.004	.169	.080	.058	.044	.044	.022	.165	.183	.075	.004	.022	.125	224
330	.003	.146	.069	.050	.061	.057	.053	.161	.140	.063	.032	.036	.121	519
ANN	.007	.087	.069	.057	.049	.048	.107	.272	.154	.047	.018	.026	.059	8698

TABLE 12A. TRANSITION MATRIX FOR DIRECTION CHANGE FOR TIME LAG OF 1 HOUR FOR LEVEL 6.

	CALM	0	30	60	90	120	150	180	210	240	270	300	330	NO.
CALM	.371	.000	.028	.000	.000	.057	.085	.142	.142	.057	.028	.000	.085	35
0	.005	.746	.141	.009	.003	.000	.000	.000	.000	.000	.001	.003	.087	754
30	.007	.114	.697	.137	.022	.003	.001	.001	.000	.000	.001	.003	.009	631
60	.002	.006	.115	.651	.175	.024	.004	.002	.008	.004	.002	.000	.002	450
90	.000	.002	.011	.123	.620	.206	.011	.005	.000	.005	.000	.005	.005	348
120	.006	.009	.000	.021	.091	.568	.273	.021	.006	.000	.003	.000	.000	329
150	.000	.002	.000	.000	.004	.053	.669	.245	.018	.000	.004	.001	.000	705
180	.000	.001	.001	.001	.001	.004	.064	.756	.157	.006	.001	.002	.001	1858
210	.001	.002	.000	.000	.000	.002	.004	.126	.754	.097	.006	.002	.001	1914
240	.000	.002	.001	.002	.001	.001	.004	.020	.210	.591	.130	.011	.019	669
270	.003	.003	.006	.003	.000	.003	.006	.010	.034	.200	.489	.162	.075	290
300	.000	.050	.022	.009	.000	.000	.004	.009	.018	.027	.146	.497	.214	219
330	.014	.211	.037	.009	.002	.002	.000	.002	.000	.014	.016	.086	.603	426
ANN	.004	.086	.073	.052	.040	.038	.082	.215	.221	.077	.034	.025	.049	8634

TABLE 12B. TRANSITION MATRIX FOR DIRECTION CHANGE FOR TIME LAG OF 24 HOURS FOR LEVEL 6.

	CALM	0	30	60	90	120	150	180	210	240	270	300	330	NO.
CALM	.032	.032	.064	.000	.000	.064	.290	.096	.225	.161	.000	.032	.000	31
0	.005	.163	.106	.071	.033	.045	.060	.067	.182	.078	.060	.033	.089	740
30	.009	.098	.136	.107	.077	.069	.090	.077	.179	.082	.026	.020	.022	630
60	.004	.061	.070	.059	.092	.103	.192	.137	.128	.064	.033	.022	.028	452
90	.002	.084	.067	.026	.034	.113	.204	.183	.139	.032	.040	.029	.040	343
120	.003	.024	.034	.009	.034	.089	.244	.291	.120	.046	.027	.034	.040	323
150	.002	.044	.017	.022	.022	.046	.194	.392	.147	.022	.022	.031	.031	703
180	.001	.058	.055	.034	.019	.013	.066	.403	.217	.052	.019	.020	.035	1835
210	.000	.068	.080	.054	.026	.009	.021	.176	.371	.095	.033	.019	.042	1878
240	.004	.089	.087	.075	.060	.022	.031	.092	.249	.154	.045	.022	.063	661
270	.013	.099	.068	.082	.082	.037	.030	.113	.174	.119	.054	.041	.082	292
300	.009	.178	.032	.032	.082	.032	.013	.128	.169	.114	.045	.041	.119	218
330	.014	.149	.071	.052	.059	.056	.049	.118	.137	.101	.049	.040	.099	422
ANN	.004	.086	.073	.052	.040	.038	.082	.215	.221	.077	.034	.025	.049	8634

south) a day later. With the exception of the 0° and 30° sectors, all surface winds are most likely to range in the 90° interval centered on south a day later. The probabilities range from 0.151 for a 330° sector wind changing to 210° a day later to 0.409 for a 180° sector wind remaining unchanged at the end of 24 hours. This is consistent with the fact that the resultant wind direction for this 1 year sample was 181° (sec. 7.1). Upper level winds show a similar tendency for southerly winds to remain southerly with 79% of the winds in the 180° sector still being southerly at the end of an hour at level 3. With the exception of the 0° and 30° sectors at level 3 and the 330° sector at level 6, upper level winds are most likely to range in the 90° interval centered on south a day later. However, while most of the surface direction categories (8 of 13) are most likely to be from the 30° sector centered on 180° after a day, wind directions at level 6 are most likely (6 of the 13 categories) to be from the sector centered on 210°, which is consistent with the fact that the resultant wind direction at level 6 for this 1 year sample was 198° (17° west of the surface resultant wind).

As the time lag increases, winds in the interval from the 60° sector through the 150° sector tend to veer more to the 180° sector, and winds in the interval from the 210° sector through the 330° sector tend to back more to the 180° sector. The tendency to back or veer increases with distance from the 180° sector. In other words, winds tend toward climatological values regardless of initial conditions. This is most noticeable after the winds have veered around to east. Winds from this direction are most likely to remain so for less than 6 hours, after which time they veer to the south in less than 18 hours. Table 10B indicates that the best statistical estimate for 240° sector winds is a 0.212 probability of changing to the 180° sector at the end of a day with only a 0.070 probability of remaining unchanged.

Surface winds least likely to occur are westerly (270° sector), which account for less than 2% of the winds in Central Oklahoma. In general, initially calm, northerly, and easterly winds seldom become westerly. At the end of 24 hours, the probabilities are 0.000, 0.060, and 0.040, respectively. This occurs because westerly winds are generally transition zone winds between warm and cold air. Fronts usually move through this area rather rapidly and are accompanied by a rapid clockwise shift of winds from south to north. Southerly surface winds, which also have low probabilities for changing to a westerly direction, are least likely to be calm at a later time. Southerly flow generally results because of the presence of lower pressure in the lee of the Rocky Mountains and the Bermuda High to the east. A west-to-east pressure gradient occurs in the mean across this area and thus prevents calm wind situations. At level 3 and 6, calm, rather than westerly winds, are least likely to occur. This is a reflection of the fact that the mean winds for the sample are some 10 kt higher at the top of the tower than at the surface. The 24-hour speed change matrix (table 6B) also shows this and indicates that all wind speeds are unlikely to be calm a day later.

6.3 Persistence of Wind Direction

Wind direction data were also analyzed for persistence, defined here as the number of observations (hours) the succeeding direction remained within a 30° sector. Persistence of wind direction was evaluated for the surface level and levels 3 and 6 on an annual and a seasonal basis. Seasons are defined as in section 5.1. Ten percent probability values for the wind direction remaining in a 30° sector for a given number of hours on an annual basis are shown in figure 18. Missing and calm observations were allowed to break persistence series but were not frequent enough to significantly affect the results.

Van der Hoven (1969) performed a similar study using 5 years of surface wind reports from 61 weather stations in the United States. He found that wind frequencies that favor a particular sector tend to persist in that sector.

Persistence values indicate how long a wind is likely to blow from a given sector while the transition matrices indicate the likelihood of a wind being from each sector at a later time. For example, a surface wind from the south (180° sector) had a 10% chance of persisting in that sector for 9.5 hours (fig. 18) and a 40.9% chance of being southerly 24 hours later (table 10B).

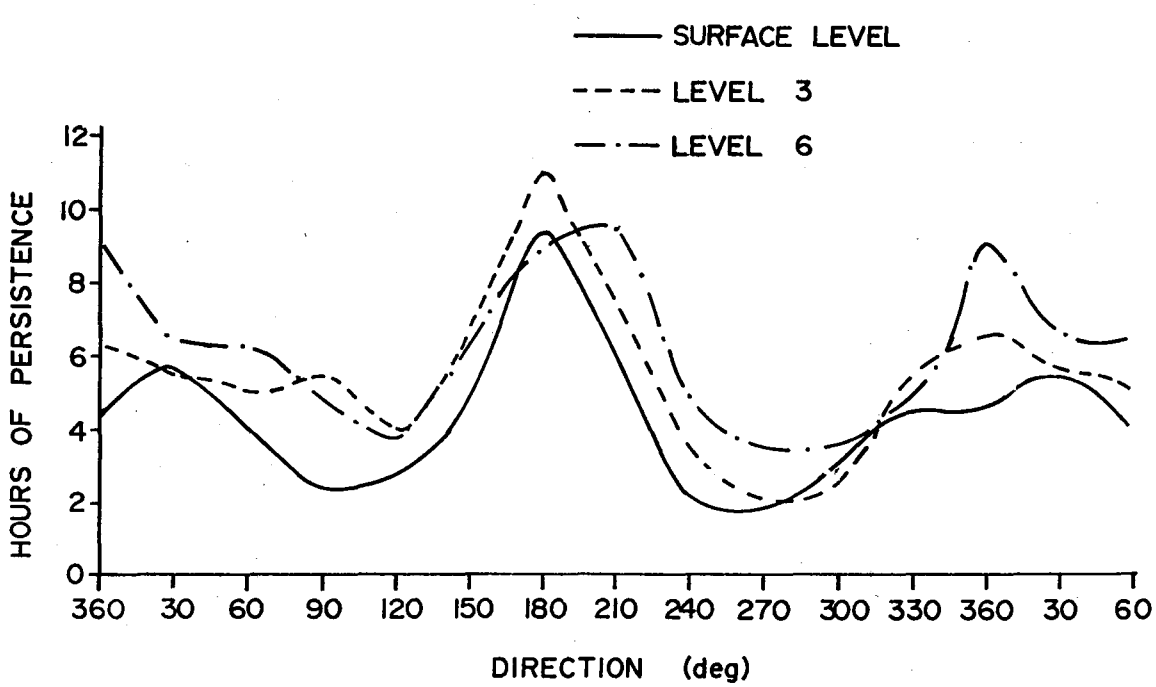


Figure 18. Ten percent probability values for the wind direction remaining in a 30° sector for a given number of hours on an annual basis.

Highest persistence values at the surface level and at level 3 are in the sector centered on 180°. The highest persistence value at level 6 is 9.5 hours centered on 210°. This shift from the 180° to the 210° sector with height corresponds to the shift in the frequency distribution of wind direction with height (sec. 6.1).

Southerly surface winds tend to persist for shorter time periods in summer than in other seasons. The 10% probability is 8.5 hours in the summer and is 10-11 hours for the other three seasons. Surface winds in the 90°, 240°, and 270° sectors have the lowest persistence. Earlier, it was noted that winds in the 90° sector have a high tendency to veer with time, and winds in the 240° and 270° sectors have a high tendency to back with time, approaching in each case the climatological mean.

The secondary peak at the surface is in the 15°-44° sector while the annual frequency distribution of wind direction (fig. 15A) indicates that the 30° sector centered on 360° has the most frequent occurrence. At levels 3 and 6, winds in the 360° sector are more frequent and tend to persist longer than those in any other sector in the northern semicircle.

The main difference between the surface and upper levels occurs for northerly winds and is most noticeable for the fall and winter seasons. For both seasons northerly winds had a 10% chance of persisting more than twice as long at the top of the tower (11 hours at level 6 and 7.5 hours at level 3) than at the surface (almost 5 hours).

In summary, the more frequent directions are also the more persistent, and, in general, persistence increases with height.

6.4 Change of Direction with Height

The change of wind direction between the surface level and level 6 was calculated on an annual basis in 30° increments for three categories: those that shifted clockwise (veered) at least 1° with height, those that shifted counterclockwise (backed) at least 1° with height, and those that did not change with height (table 13). Cases with calm winds at either level were not included.

TABLE 13. PROBABILITIES FOR WIND DIRECTION CHANGE BETWEEN THE SURFACE LEVEL AND LEVEL 6.

SFC WIND (DEG)	BACKING WITH HT	NO CHANGE WITH HT	VEERING WITH HT	NO. OF OBS.
15- 44	.237	.016	.747	502
45- 74	.225	.016	.759	423
75-104	.287	.015	.698	331
105-134	.175	.010	.815	422
135-164	.115	.013	.872	1046
165-194	.122	.014	.863	2366
195-224	.229	.011	.760	1046
225-254	.344	.021	.635	241
255-284	.293	.020	.687	150
285-314	.224	.011	.765	357
315-344	.194	.012	.794	674
345- 14	.212	.033	.755	645
ALL DIR	.184	.015	.801	6572

165°-194°, 50% of the backing winds back by 5° or less and 50% of the veering winds veer by 18° or less. These tables also indicate that the more frequently observed directions tend to veer and back less with height than do the less frequently observed directions, i.e., as noted above, there is a tendency for the directions to approach the annual distributions.

6.5 Annual Relative Frequency Distributions for Various Speed Intervals

Frequency distributions of wind direction in 10° intervals for five speed classes--0.1-10 kt, 10.1-20 kt, 20.1-30 kt, 30.1-40 kt, and greater than 40 kt--were determined and compared with the frequency distributions of wind direction for all non-zero speeds. These data were then summarized into 4 direction intervals centered on 0°, 90°, 180°, and 270° (table 15). Since

TABLE 15. ANNUAL RELATIVE FREQUENCY DISTRIBUTIONS OF WIND DIRECTION FOR VARIOUS SPEED INTERVALS FOR THE 7 LEVELS.

		ALL NON-ZERO SPEEDS	0.1-10 KT	10.1-20 KT	20.1-30 KT	30.1-40 KT	GREATER THAN 40 KT
		%	%	%	%	%	%
	N	22.7	20.9	25.2	43.9	0.0	0.0
LEV	E	14.3	18.7	6.0	1.2	0.0	0.0
	S	53.9	49.0	64.2	46.8	0.0	0.0
SFC	W	9.1	11.4	4.6	8.1	0.0	0.0
	NO	8314	5445	2696	173	0	0
	N	23.6	26.4	21.2	21.1	56.2	0.0
LEV	E	14.6	23.7	8.6	0.8	6.2	0.0
	S	53.5	38.7	64.0	73.4	25.0	0.0
1	W	8.3	11.2	6.2	4.7	12.6	0.0
	NO	8599	3848	3945	790	16	0
	N	24.2	29.5	20.3	17.3	31.9	0.0
LEV	E	15.2	24.5	14.7	1.2	1.1	0.0
	S	53.2	32.5	57.4	77.1	57.4	0.0
2	W	7.4	13.5	7.6	4.4	9.6	0.0
	NO	8653	2572	4587	1400	94	0
	N	21.7	27.3	23.5	14.7	13.5	20.0
LEV	E	15.6	24.3	18.0	5.1	1.8	20.0
	S	53.6	33.2	51.0	73.7	80.7	60.0
3	W	9.1	15.2	7.5	6.5	4.0	0.0
	NO	8635	2235	3753	2367	275	5
	N	21.3	26.6	25.7	16.3	6.7	8.6
LEV	E	15.0	23.3	19.6	6.0	2.0	3.5
	S	53.0	33.1	45.8	68.3	85.8	84.4
4	W	10.7	17.0	8.9	9.4	5.5	3.5
	NO	8591	2140	3231	2256	906	58
	N	21.0	25.5	25.8	18.9	8.1	2.8
LEV	E	14.1	22.9	19.4	6.6	2.0	1.2
	S	53.0	33.7	44.2	63.0	82.1	90.7
5	W	11.9	17.9	10.6	11.5	7.8	5.3
	NO	8651	1875	3212	2220	1023	321
	N	21.0	24.9	25.9	19.0	10.1	2.7
LEV	E	13.2	21.6	18.2	6.0	1.5	1.1
	S	52.1	36.1	43.1	61.1	76.2	89.8
6	W	13.7	17.4	12.8	13.9	12.2	6.4
	NO	8599	1796	3072	2139	963	449

TABLE 16. THE RESULTANT WIND VECTOR AND THE STEADINESS OF THE WIND DIRECTION ON A MONTHLY AND AN ANNUAL BASIS.

LEVEL	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	YEAR
MAGNITUDE OF THE RESULTANT WIND VECTOR (KT)													
6	15.4	13.6	8.1	2.9	7.7	12.4	4.6	8.8	6.1	11.3	14.8	5.3	8.7
5	15.7	13.7	8.2	3.0	7.6	11.6	3.8	7.7	5.9	10.3	13.7	5.3	8.4
4	14.6	12.9	7.4	2.9	6.6	10.6	2.9	6.4	4.9	9.0	12.4	4.9	7.6
3	13.5	11.2	6.5	2.0	5.9	8.4	2.0	5.0	4.5	7.7	11.2	4.3	6.5
2	11.3	9.4	5.5	1.5	5.0	6.7	2.0	4.4	3.4	6.1	9.1	3.3	5.2
1	9.0	7.7	4.5	1.0	4.0	5.6	1.8	3.6	2.4	4.5	7.8	2.8	4.2
SFC	6.1	4.9	2.6	0.3	2.5	3.6	1.3	2.7	1.1	2.7	5.7	1.4	2.6
DIRECTION OF THE RESULTANT WIND VECTOR (DEG)													
6	180	190	185	192	212	212	235	232	240	193	178	179	198
5	177	185	182	191	207	207	237	225	227	190	173	174	193
4	175	182	177	177	197	202	238	219	218	183	169	171	187
3	172	175	169	168	191	194	239	216	210	177	164	165	181
2	171	170	161	171	193	193	260	223	219	177	167	165	181
1	169	168	163	165	198	195	257	219	214	175	169	164	181
SFC	167	166	160	55	208	204	280	218	232	176	171	143	181
STEADINESS													
6	0.81	0.85	0.56	0.23	0.39	0.54	0.28	0.41	0.31	0.55	0.60	0.29	0.46
5	0.79	0.86	0.55	0.23	0.39	0.52	0.23	0.37	0.31	0.49	0.57	0.29	0.45
4	0.78	0.85	0.60	0.25	0.37	0.52	0.19	0.34	0.27	0.48	0.57	0.29	0.44
3	0.81	0.85	0.53	0.19	0.36	0.48	0.15	0.29	0.28	0.43	0.57	0.28	0.42
2	0.77	0.83	0.49	0.16	0.34	0.43	0.16	0.29	0.23	0.40	0.56	0.25	0.38
1	0.76	0.83	0.50	0.13	0.34	0.42	0.17	0.29	0.19	0.37	0.56	0.25	0.37
SFC	0.74	0.80	0.43	0.06	0.30	0.38	0.17	0.30	0.12	0.28	0.55	0.17	0.32

187°/7.6 kt, 193°/8.4 kt, and 198°/8.7 kt. Note that the resultant direction is 181° for each of the lowest four levels and that the annual arithmetic mean speed is greater than the annual resultant wind speed. The annual resultant speed is about 32% of the arithmetic mean speed at the surface (i.e., the steadiness value is 0.32) and increases upward to the top level to a value of 46%. Thus, the variability of the wind direction decreases with height.

Monthly values of the resultant wind speed vary from 6% of the arithmetic mean at the surface level in September to 86% at level 5 in July (table 16). In general, winds during June and July were the steadiest. September, December, February, and May, which were months with lighter winds than the surrounding months, were the least steady.

7.2 Diurnal Variations

The diurnal oscillation of the resultant directions for the surface, level 4, and level 6 is shown in figure 19. Of the lowest four levels, only the surface level is plotted since the four curves of the resultant direction were almost identical. This agrees with the annual resultant wind vector given in table 16, which has a direction of 181° at the four levels.

All direction categories show a strong tendency to veer with height. When all directions were considered, 80.1% veered, 18.4% backed, and 1.5% did not change with height. It was noted in section 6.1 that the frequency distributions of direction appear to shift about 10°-20° clockwise between the bottom and the top of the tower. An analysis of backing and veering in 10° increments of direction change with height showed that 18.8% of the winds veered between 1° and 10°, 19.0% veered between 11° and 20°, and 14.1% veered between 21° and 30°. No backing and no other veering categories of direction change with height in 10° increments exceeded 10.0%.

Veering was most frequent and backing least frequent in the interval 135°-164°, and backing was most frequent and veering least frequent in the interval 225°-254°. This suggests that while the winds tend to veer with height, they also tend to shift to the most frequent direction interval.

Table 14A shows the cumulative relative frequencies for all cases that veered with height, and table 14B shows the cumulative relative frequencies for all cases that backed with height. The basic tendency for winds to veer with height is shown here by the fact that, in general, the direction change with height at the given probability levels is less for backing cases than for veering cases. For example, in the surface wind category

TABLE 14A. CUMULATIVE RELATIVE FREQUENCY DISTRIBUTIONS FOR WIND DIRECTION CHANGE BETWEEN THE SURFACE LEVEL AND LEVEL 6 WHEN VEERING WITH HEIGHT.

SFC WIND (DEG)	50 %	75 %	90 %	95 %
15- 44	18°	34°	63°	115°
45- 74	27	55	97	121
75-104	37	66	97	115
105-134	31	56	81	99
135-164	22	36	56	72
165-194	18	31	43	53
195-224	18	35	58	80
225-254	33	57	80	112
255-284	36	52	76	92
285-314	36	62	89	108
315-344	26	52	89	108
345- 14	15	29	69	102

TABLE 14B. CUMULATIVE RELATIVE FREQUENCY DISTRIBUTIONS FOR WIND DIRECTION CHANGE BETWEEN THE SURFACE LEVEL AND LEVEL 6 WHEN BACKING WITH HEIGHT.

SFC WIND (DEG)	50 %	75 %	90 %	95 %
15- 44	8°	18°	71°	141°
45- 74	12	26	47	82
75-104	13	34	52	92
105-134	14	24	45	57
135-164	7	17	39	53
165-194	5	12	24	33
195-224	7	14	25	34
225-254	14	33	58	77
255-284	22	38	81	89
285-314	48	72	110	130
315-344	16	101	134	155
345- 14	7	22	104	152

oscillation, the backing and veering of the wind vector with time during a day, was also apparent in the WKY data. Except for minor interruptions around sunrise, the winds at all levels veer with time between 2100 and approximately 1100 CST. Wind directions then back with time between approximately 1100 and 2000 CST. The onset of backing begins first at level 6 at 0900 CST and works downward to the surface where backing begins at 1100 CST. Backing winds generally end at all levels except level 6 by 2000 CST. Thus winds at each level veer approximately 14 hours a day and back 10 hours a day with the wind vector returning to its starting point at the end of the day; consequently, the average rate of backing at each level was greater than the rate of veering during this 1 year period. Backing with time was generally at a maximum between 1600 and 1800 CST and a minimum between 1200 and 1400 CST. Veering with time was at a maximum just before midnight and a minimum just after sunrise. Hour-to-hour changes in the resultant direction at level 6 were more uniform than those below this level. Magnitudes of the resultant direction oscillation ranged from 54° at the surface to 38° at level 4 to 40° at level 6.

Deviations of the hourly resultant components from the annual resultant components were computed for each hour of the 24-hour cycle (fig. 20A-B) in order to give a more detailed description of the diurnal oscillation in the boundary layer winds. This approach was used to provide a direct comparison with the work of Bonner and Paegle (1969) in their study of 11 years of summertime rawinsonde data at Fort Worth, Texas. The results, which should have been the same by using either the actual resultant vectors or the deviation resultant vectors, are in good agreement with Bonner and Paegle's work and provide a more detailed analysis of the boundary-layer wind oscillation. The v' component showed a maximum daily variation of almost 8 kt between levels 5 and 6, and the maximum variation of the u' component was at least 6.5 kt and occurred above level 6. Southerly winds were a maximum at midnight and a minimum at 1100 CST. Westerly winds were a maximum at 0600 CST at level 6 and gradually worked downward to where westerly surface winds were a maximum at 1100 CST. The amplitude of the u' component was greater than the amplitude of the v' component below level 3. The reverse was true above level 3.

Hodographs of the data in figure 20 are shown (fig. 21A-D) for the surface, and levels 2, 4, and 6. Except for the surface level, all hodographs show anticyclonic rotation of the deviation vector at a rate that is greatest between approximately 1700-0400 CST. This can also be seen in the diurnal oscillation of the resultant directions (fig. 19). These hodographs are ellipsoidal in shape near the surface and become more circular at the higher tower levels. This agrees, in part, with Bonner and Paegle who found that their hodographs were nearly circular at elevations (AGL) of 0.15 km (492 ft) and 0.32 km (1050 ft).

8. WIND SHEAR

8.1 Monthly and Annual Distributions

Statistics of the wind shear, defined as the change of the wind vector with height, were calculated for each layer bounded by successive levels.

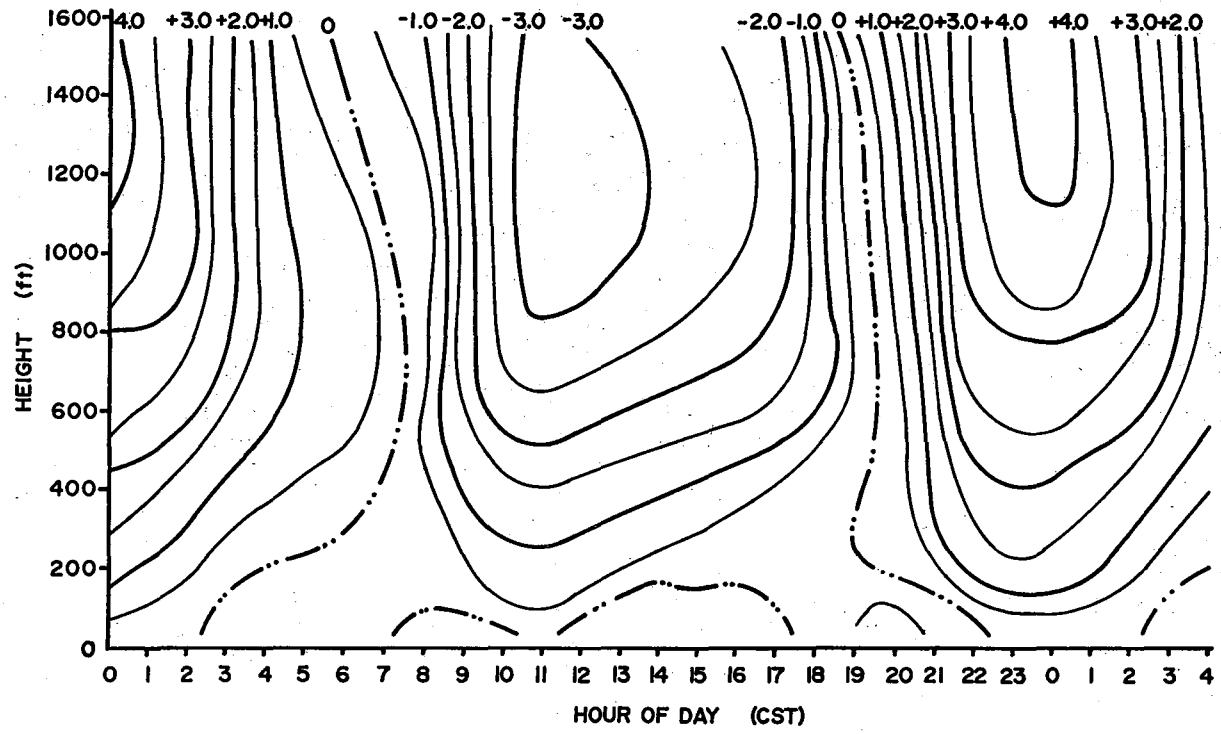


Figure 20A. Diurnal variation of the deviations of the hourly resultant components from the annual resultant components for the 7 levels (v' component).

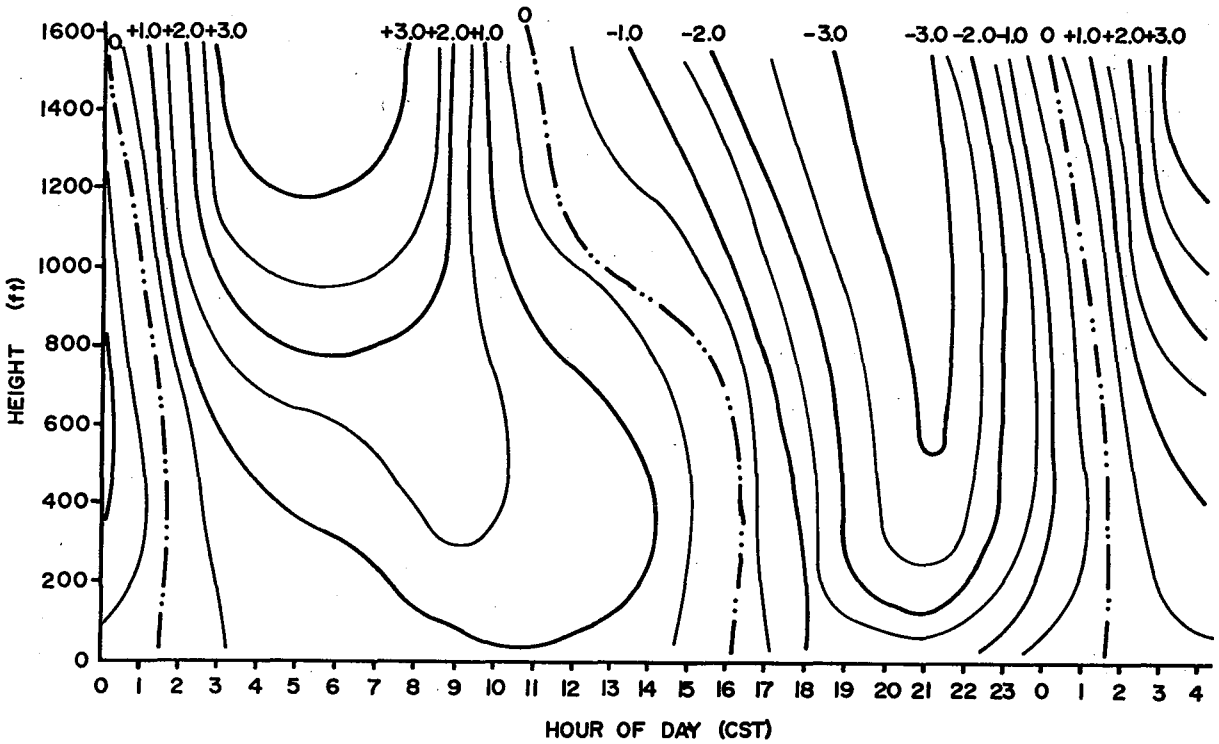
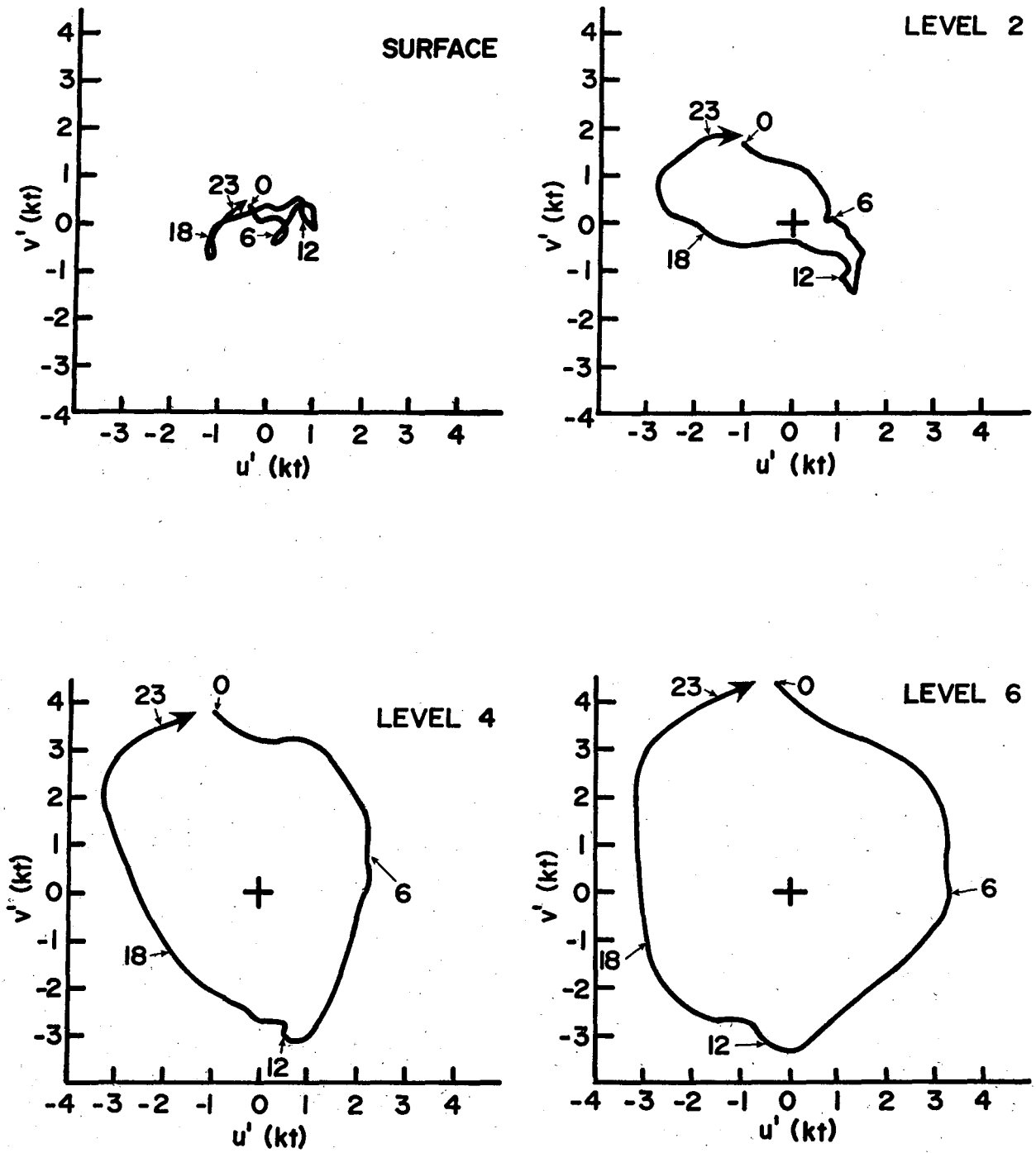


Figure 20B. Diurnal variation of the deviations of the hourly resultant components from the annual resultant components for the 7 levels (u' component).



Figures 21 A-D. Hodographs of the deviation vector (see figs. 20A&B) for A) surface level, B) level 2, C) level 4, and D) level 6.

The wind shear for a layer was calculated by resolving the wind observations at the top (subscript i + 1) and bottom (subscript i) of the layer into north-south (u) and east-west (v) components, obtaining the difference of each component between the top and the bottom of the layer, dividing the differences by the thickness of the layer, and converting the results into a single vector:

$$\frac{\partial \vec{V}}{\partial Z} \approx \frac{\Delta \vec{V}}{\Delta Z} = \left[\frac{u_{i+1} - u_i}{Z_{i+1} - Z_i}\right] \vec{i} + \left[\frac{v_{i+1} - v_i}{Z_{i+1} - Z_i}\right] \vec{j}, \qquad (7)$$

In order of increasing height above the base of the tower, the thickness of the layers are: (1) 106 ft, (2) 150 ft, (3) 285 ft, (4) 292.5 ft, (5) 292.5 ft, and (6) 292.5 ft. The values of shear represent the shear of the 5-minute mean wind rather than the maximum values of shear during the 5-minute period.

Figure 22 shows the annual relative frequency distribution of wind shear speed per 100 ft in 1 kt intervals and the number of events for intervals in which the frequency was less than 1%. Wind shear values in layer 1 are fairly evenly distributed over the range 0-6 kt per 100 ft with the maximum number of occurrences in the interval 3-4 kt per 100 ft. The highest percentage in layer 2 occurs in the 1-2 kt interval. In all other layers the highest percentage occurs in the 0-1 kt interval with the percentage in this interval increasing with height to a maximum of 61.2% of the events in layer 6. There were 3 events in layer 1 with shear greater than 11 kt/100 ft and one greater than 12 kt/100 ft.

The cumulative relative frequency of the wind shear speed being equal to or less than a given value was determined. Probabilities are given for the 75%, 95%, and 99% levels (table 17).

In layer 1, 25% of the wind shear speeds exceeded 5.1 kt/100 ft, 5% exceeded 7.1 kt/100 ft, and 1% exceeded 8.7 kt/100 ft. It is interesting to note that the shear speeds at the 99% level in layers 4 and 5 exceeded that in layer 3 by 0.3 kt/100 ft and deviated from the statistical pattern of the wind shear decreasing with height for each probability level. This deviation is a result of the inflection point at level 3 in the wind speed profile (figs. 9 and 12).

TABLE 17. CUMULATIVE RELATIVE FREQUENCY DISTRIBUTIONS FOR ARITHMETIC WIND SHEAR SPEED (KT/ 100 FT).

LAYER	HEIGHT(FT)	THICKNESS(FT)	75%	95%	99%
1	40-146	106	5.1	7.1	8.7
2	146-296	150	2.8	4.4	5.5
3	296-581	285	1.7	2.9	3.7
4	581-874	293	1.7	2.9	4.0
5	874-1166	292	1.5	2.8	4.0
6	1166-1458	292	1.4	2.8	3.6

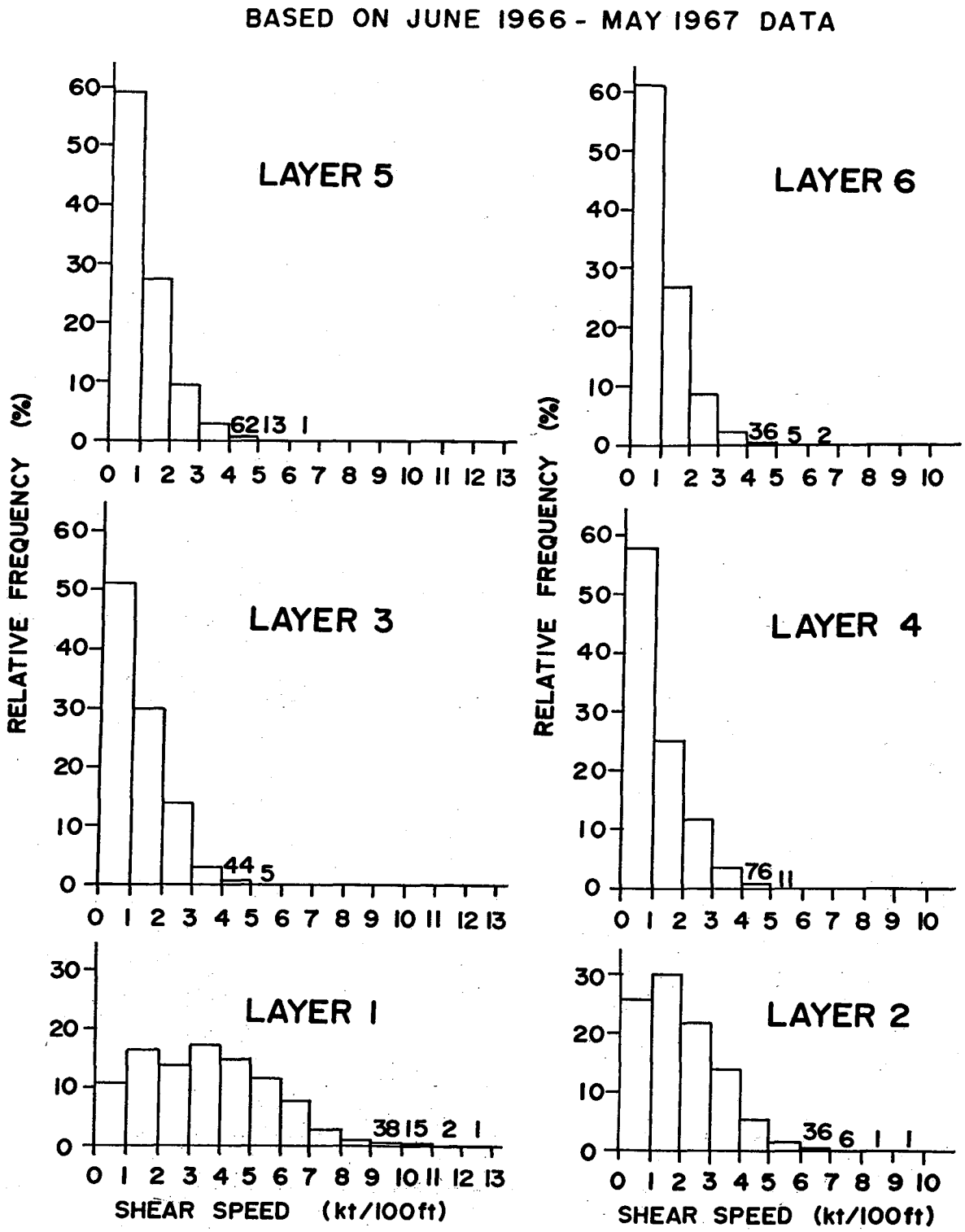


Figure 22. Annual relative frequency distribution of wind shear speed per 100 ft for the 6 layers. The number of events for categories with less than 1% of the events are shown.

The annual arithmetic mean shear speed, defined in a manner analogous to arithmetic mean speed, is 3.58 kt/100 ft in layer 1, 1.98 kt/100 ft in layer 2, 1.18 kt/100 ft in layer 3, and decreases slowly with height to 0.95 kt/100 ft in layer 6 (table 18).

Monthly values of the arithmetic mean shear speed are listed for all layers in table 18 and are plotted for layers 1, 2, and 6 in figure 23. Values for layers 3, 4, and 5 range from 0.85 kt/100 ft in layer 5 in September to 1.50 kt/100 ft in layer 3 in April. The shear speed in the lower layers varies considerably from month to month in the data used in this study, and the shear speed in the upper layers changes little. The month to month variability of the arithmetic mean speed increases with height (fig. 10), and the variability of the arithmetic mean shear speed decreases with height.

TABLE 18. ARITHMETIC MEAN SHEAR SPEED AND THE RESULTANT SHEAR VECTOR ON A MONTHLY AND AN ANNUAL BASIS.

	HT. AT LAYER TOP	LAYER THICK-NESS	ARITHMETIC MEAN SHEAR SPEED (KT/ 100 FT)												
LYR	(FT)	(FT)	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	YEAR
6	1458	292	0.82	0.82	0.72	0.73	0.82	0.97	1.19	1.26	1.08	1.06	1.17	0.81	0.95
5	1166	292	0.86	0.86	0.88	0.85	1.22	1.15	1.06	1.37	1.11	1.25	1.21	1.06	1.08
4	874	293	1.03	1.09	0.95	0.87	1.04	1.42	1.13	1.32	1.05	1.19	1.19	1.00	1.11
3	581	285	1.09	1.09	1.00	0.94	1.25	1.26	1.04	1.30	1.10	1.41	1.50	1.17	1.18
2	296	150	1.99	1.65	1.76	1.65	2.15	1.87	1.88	2.62	2.11	2.30	1.87	1.87	1.98
1	146	106	3.96	3.21	3.08	2.87	4.30	3.98	3.63	3.89	3.49	3.29	3.60	3.65	3.58
TWR	1458	1418	1.28	1.21	1.14	1.08	1.44	1.48	1.38	1.64	1.37	1.49	1.50	1.30	1.36
	HT. AT LAYER TOP	LAYER THICK-NESS	RESULTANT MEAN SHEAR SPEED (KT/ 100 FT)												
6	1458	292	0.34	0.41	0.18	0.09	0.26	0.43	0.21	0.48	0.32	0.25	0.52	0.14	0.28
5	1166	292	0.32	0.35	0.36	0.19	0.47	0.50	0.31	0.53	0.45	0.58	0.59	0.17	0.38
4	874	293	0.67	0.76	0.43	0.28	0.35	0.86	0.32	0.48	0.29	0.46	0.51	0.26	0.46
3	581	285	0.63	0.67	0.40	0.21	0.34	0.57	0.26	0.28	0.32	0.56	0.77	0.27	0.42
2	296	150	1.27	1.22	0.75	0.49	0.67	0.82	0.19	0.54	0.60	0.93	0.86	0.45	0.65
1	146	106	3.03	2.59	1.80	0.97	1.84	1.78	0.67	0.99	1.56	1.58	2.15	1.56	1.65
TWR	1458	1418	0.67	0.66	0.40	0.22	0.39	0.62	0.27	0.42	0.38	0.52	0.66	0.30	0.44
	HT. AT LAYER TOP	LAYER THICK-NESS	DIRECTION OF MEAN RESULTANT SHEAR VECTOR (DEG)												
6	1458	292	285	280	290	322	291	263	227	284	299	244	224	271	268
5	1166	292	198	225	219	219	261	250	233	253	260	227	210	209	233
4	874	293	199	216	222	224	231	228	235	226	236	229	204	206	220
3	581	285	180	199	203	154	179	201	156	175	199	174	156	156	180
2	296	150	174	182	152	165	175	181	277	243	230	181	150	172	180
1	146	106	174	171	169	183	191	189	218	220	197	171	167	179	181
TWR	1458	1418	189	202	196	193	215	218	222	239	233	200	183	188	205

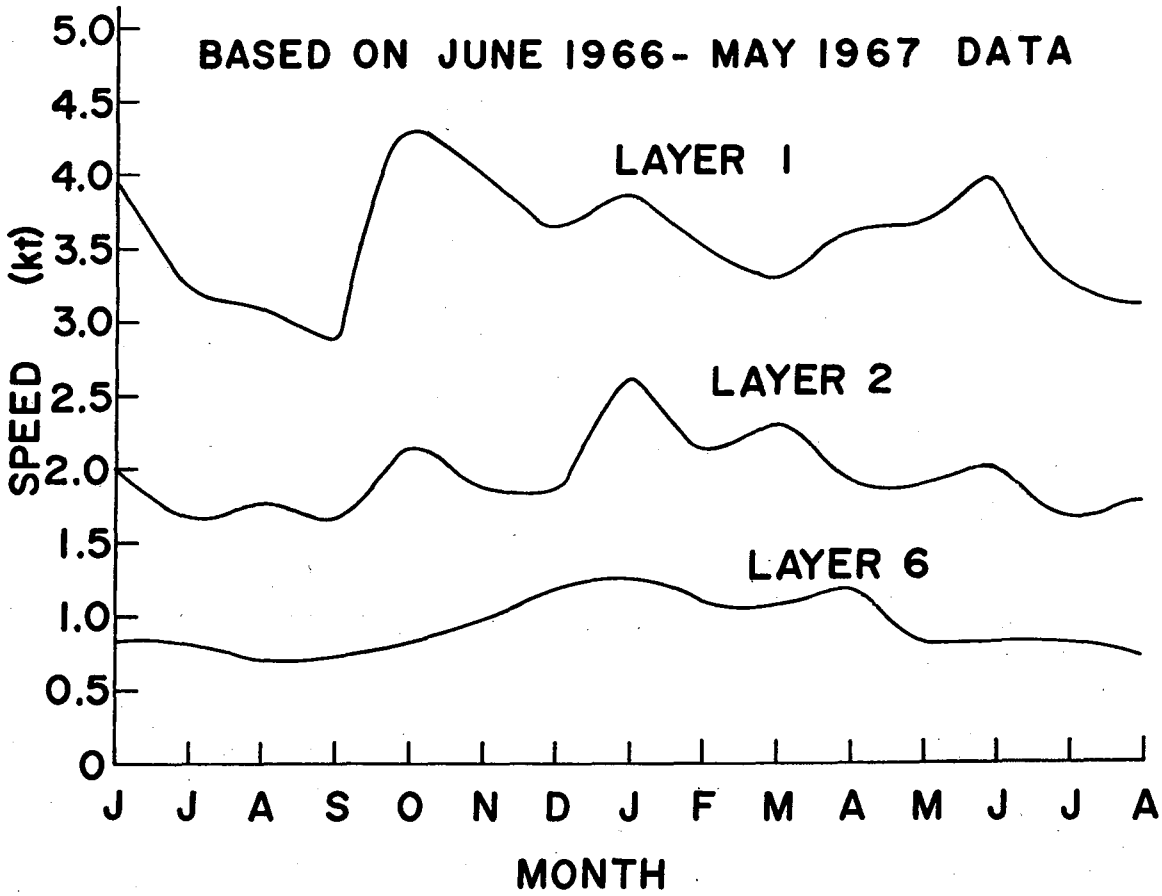


Figure 23. Monthly arithmetic mean shear speed (kt per 100 ft) for layers 1, 2, and 6.

The average shear speed in the tower layer (layer called tower layer in table 18) for the year was 1.36 kt/100 ft. It was calculated using

$$\frac{\sum_{i=1}^{6}\left(\overline{\left|\frac{\partial \vec{V}}{\partial Z}\right|_i} * \Delta H_i\right)}{\sum_{i=1}^{6} \Delta H_i}, \qquad (8)$$

where $\overline{\left|\frac{\partial \vec{V}}{\partial Z}\right|_i}$ is the annual arithmetic shear speed per 100 ft in layer i and ΔH_i is the thickness of layer i. The maximum monthly value is 1.64 kt/100 ft in January, and the minimum monthly value is 1.08 kt/100 ft in September.

The annual resultant shear speed, defined in a manner analogous to resultant speed, is considerably less than the annual arithmetic mean shear speed because of the cancelling effect of opposing winds. The resultant

speed was less than the arithmetic mean speed for the same reason. The annual resultant shear vector with speeds in kt per 100 ft is 181°/1.65 in layer 1, 180°/0.65 in layer 2, 180°/0.42 in layer 3, 220°/0.46 in layer 4, 233°/0.38 in layer 5, and 268°/0.28 in layer 6. Values of the average resultant shear vector in the tower layer are also given in table 18. The direction of the annual resultant shear vector is south in the lowest three layers and is the same as the direction of the annual resultant wind vector (table 16). Thus, in the lowest three layers the wind shear is mostly speed shear. In the upper three layers, the wind shear is a combination of direction and speed shear.

8.2 Diurnal Variations

Figure 24 shows the annual diurnal distribution of the arithmetic shear speed, and figure 25 shows the annual diurnal distribution of the resultant shear vector. Both distributions are characterized by a large minimum centered at 1400 CST in the middle layers and maximum values near midnight in the lowest layers. This is in agreement with the distribution of arithmetic mean speed (fig. 11). The shear speed changes most rapidly with height in the lowest two layers. The most rapid increase occurs near sunset, and the most rapid decrease occurs near sunrise. During the daylight hours, the shear speed is nearly constant with height (but not with time) in the upper three layers. Earlier, it was shown that the increase in wind speed with height (fig. 11) and the change in the resultant direction with height (fig. 19) are much greater at night than during the day. This implies that both speed and direction shear are greatest at night.

Monthly diurnal distributions show the same general features with the rapid increase and decrease maintaining their positions relative to sunrise and sunset. A more detailed discussion of the behavior of the wind on a diurnal basis was given in section 5.5 and section 7.2.

9. SUMMARY AND CONCLUSIONS

The annual arithmetic mean wind speed increases with height from 8.1 kt at the surface level (23 ft AGL) to 18.7 kt at the top level (1458 ft AGL). The rate of increase of speed with height decreases with height so that the annual speeds at levels 5 and 6 differ by only 0.1 kt (fig. 9), which suggests that frictional effects must be small at the top of the tower.

There is considerable month-to-month variability of the values of the arithmetic mean speed (fig.10). This variability increases with height.

On an annual basis at the two lower tower levels, the arithmetic mean speed is at a minimum near midnight and a maximum near 1400 CST (figs. 11 and 12). It is at a maximum near midnight and a minimum during midday at levels 2 through 6. Most of the speed change occurs in a short period just after sunrise and just before sunset and is probably associated with the onset and cessation of convective mixing.

The annual gust factor decreases with height from a value of 1.53 at the surface to 1.17 at levels 5 and 6 (table 9). The gust factor is a

maximum at all levels at midday and a minimum at night (fig. 14).

The annual frequency distributions of wind direction are bimodal with most of the winds being either southerly or northerly (fig. 15A-G). For the tower layer, approximately 53% of the winds were from the southern quadrant, 22% from the northern quadrant, 14% from the eastern quadrant, 10% from the western quadrant, and 1% calm. Percentages at individual levels differ from these values by less than 3%. The primary peak is in the 10° interval

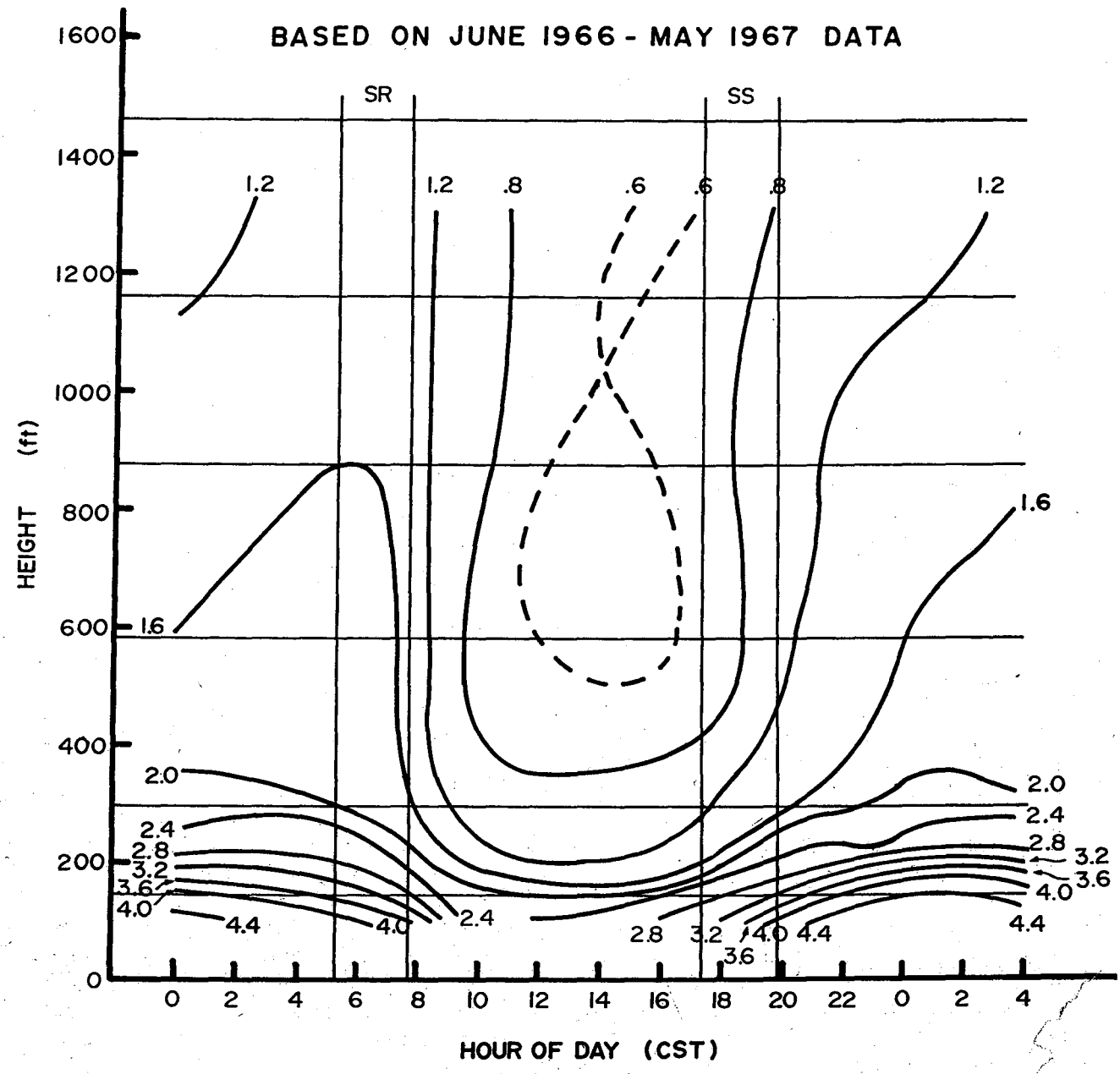


Figure 24. Diurnal variations of the arithmetic shear speed (kt per 100 ft) on an annual basis.

centered on 180° at the lowest 3 levels and on 190° at the upper 4 levels. The secondary peak varies in location from 340° through north to 20° and, in general, shows a clockwise shift with height. The likelihood of the wind direction being southerly increases as the speed increases (table 15).

There is considerable variability of wind direction from month to month (figs. 16A-L and 17A-L). Generally, northern and eastern quadrant winds are

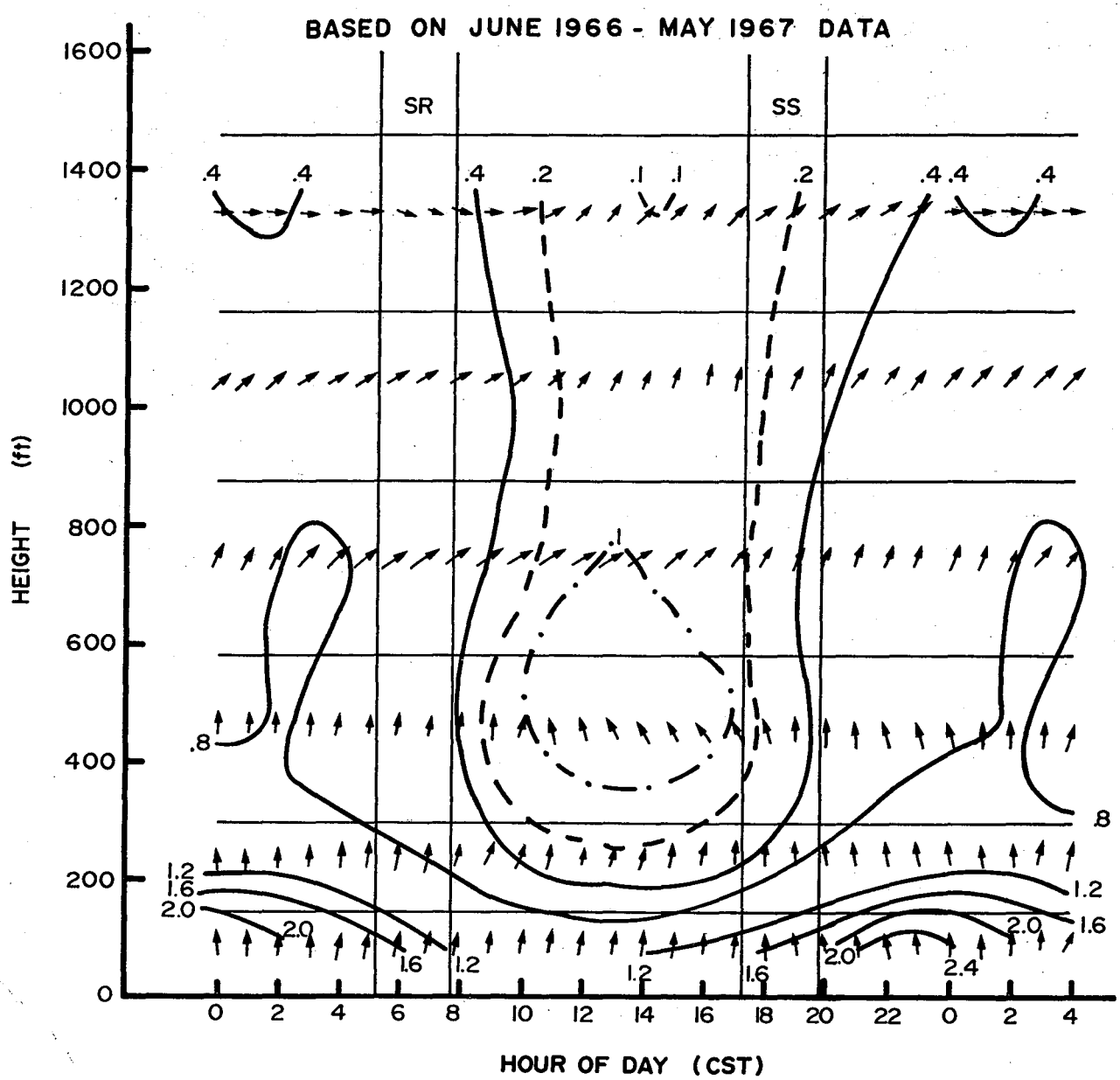


Figure 25. Diurnal variations of the resultant shear vector on an annual basis. Lines are isotachs of resultant speed (kt per 100 ft). Arrows represent the resultant shear direction.

more frequent in the winter half of the year (October-March) than in the summer half of the year; southern and eastern quadrant winds are more frequent in the summer half than in the winter half.

Annual resultant wind speeds increase with height from 2.6 kt at the surface to 8.7 kt at the top level. The direction of the resultant vector is 181° at the lowest 4 levels and veers uniformly above to 198° at the top. The variability of the wind direction decreases with height.

The resultant vector veers with height during most hours of the day. Maximum veering with height is 30° at 0600 CST and minimum veering with height occurs during midday with backing below level 3 (fig. 19).

Winds veer with time between 2100 and 1000 CST and back with time during the remaining hours. Maximum veering with time occurs just before midnight and maximum backing between 1600 and 1800 CST (fig. 19).

Wind shear speeds decrease with height, more rapidly in the lower layers than in the upper layers. The annual arithmetic mean shear speed varied from 3.58 and 1.98 kt per 100 ft in layers 1 and 2, respectively, to approximately 1 kt per 100 ft in the upper 4 layers (table 18). The month-to-month variability of the arithmetic mean shear speed decreases with height (fig. 23) and that of the arithmetic mean wind speed increases with height (fig. 10).

The direction of the annual resultant shear vector is 181° in the lowest 3 layers. This primarily reflects speed shear while the resultant shear in the top 3 layers is a combination of speed and direction shear.

The annual diurnal distributions of the arithmetic (fig. 24) and the resultant shear speeds (fig. 25) are characterized by a large minimum centered at 1400 CST in the middle layers and by maximum values near midnight in the lowest layers.

10. ACKNOWLEDGEMENTS

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Mr. Leonard Johnson has maintained the equipment at the tower since the start of the NSSL-WKY tower project. Mr. Curtis Smith drafted the figures, Mr. Charles Clark photographed the figures and tables, and Mrs. Joy Walton typed the manuscript.

Dr. Edwin Kessler suggested this study, provided guidance, and reviewed the manuscript.

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NATIONAL SEVERE STORMS LABORATORY

The NSSL Technical Memoranda, beginning with No. 28, continue the sequence established by the U. S. Weather Bureau National Severe Storms Project, Kansas City, Missouri. Numbers 1-22 were designated NSSP Reports. Numbers 23-27 were NSSL Reports, and 24-27 appeared as subseries of Weather Bureau Technical Notes. These reports are available from the Clearinghouse for Federal Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22151, for $3.00, and a microfiche version for $0.65. CFTSI numbers are given below in parentheses.

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No. 3 Instability Lines and Their Environments as Shown by Aircraft Soundings and Quasi-Horizontal Traverses. D. T. Williams. February 1962. (PB-168209)

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