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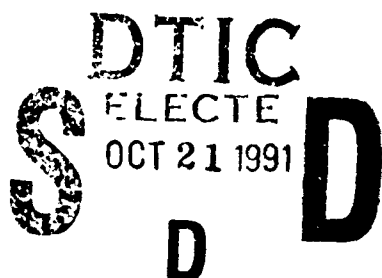
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A Statistical Analysis of Eleuthera Island Wind Data for the Period 27 April 1989 Through 30 March 1990

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Test and Evaluation Department

J. J. Hinkamp
General Electric Co.



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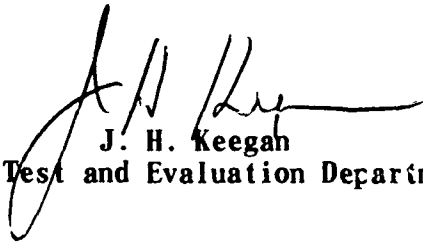


Naval Underwater Systems Center
Newport, Rhode Island · New London, Connecticut

PREFACE

This study was conducted by the Test and Evaluation Department (Code 38) under AUTECH Job Order 696704.

REVIEWED AND APPROVED: 1 JULY 1991

A handwritten signature in black ink, appearing to read 'J. H. Keegan', is written over the printed name.

J. H. Keegan
Head, Test and Evaluation Department

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13. ABSTRACT (Maximum 200 words) This document presents a statistical analysis of wind data obtained at Eleuthera Island, Bahamas, during the period between April 1989 and March 1990. The analysis is limited to empirically determined probability distribution and density functions, first- and second-moment estimators, and one-dimensional Fourier transforms, appropriately averaged for power spectral estimates. Broad conclusions are drawn about the variability of wind speed, the predominant wind direction, and the pattern of wind speed during specified intervals.				
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A STATISTICAL ANALYSIS OF ELEUTHERA ISLAND WIND DATA FOR THE PERIOD 27 APRIL 1989 THROUGH 30 MARCH 1990

INTRODUCTION

This report presents a compilation and statistical analysis of wind speed and direction data observed from 27 April 1989 through 30 March 1990 at Eleuthera Island, Bahamas. Wind measurements were recorded at 10-minute intervals during periods of instrumentation operability. Each wind sample consisted of date-time, average speed (m/sec), maximum speed (m/sec), and bearing (degrees). The data were stored digitally in a random access memory (RAM) contained in the instrumentation and recovered by use of a serial connection to a personal computer (PC).

The statistical analysis of the data is limited to empirically determined probability distribution and density functions, first- and second-moment estimators, and one-dimensional Fourier transforms, appropriately averaged for power spectral estimates.



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DATA COLLECTION

DATA MEASUREMENT SITE

The data measurement site was an abandoned Air Force communications base on Eleuthera Island. The latitude and longitude of the site are 25°17'56" N and 76°18'56" W. Figure 1 is a contour map of the site. The sensors were placed on top of a building located approximately 1000 feet from the beach. The elevation of the building site is about 80 feet and the building height is about 30 feet. The sensors were supported on a 10-foot mast at the top of the building. At the sensor elevation of approximately 120 feet, the line of sight was clear except for a line of Australian pines located to the northeast. The general location of the trees is also shown in figure 1.

MEASUREMENT INSTRUMENTATION

A suite of sensors and data loggers manufactured by Aanderaa Instruments comprised the measurement equipment. The sensors consisted of wind speed and direction sensors. The analog outputs from these sensors are read by a scanning unit and directly approximated to a digital 10-bit data word by use of a pulsed bridge system. The scanning unit controls the data acquisition interval. The digital information is recorded into a data storage unit of static RAMs. The digital data are then downloaded to a PC for storage and processing. Pertinent specifications for each unit are presented below.

1. Wind Speed Sensor 2740:

Threshold Speed : 0.58 - 0.97 knot
Range : 116 knots
Accuracy : < 2 percent or 0.39 knot

2. Wind Direction Sensor 2750:

Threshold Speed : < 0.58 knot
Accuracy : < 5°

3. Sensor Scanning Unit 3010: The sampling interval for this unit was set to 10 minutes. At the expiration of each interval, the scanning unit triggers a data acquisition cycle. The present bridge voltage from each sensor is pulsed 10 times, with each pulse requiring 1/36 second, to provide the digital approximation.

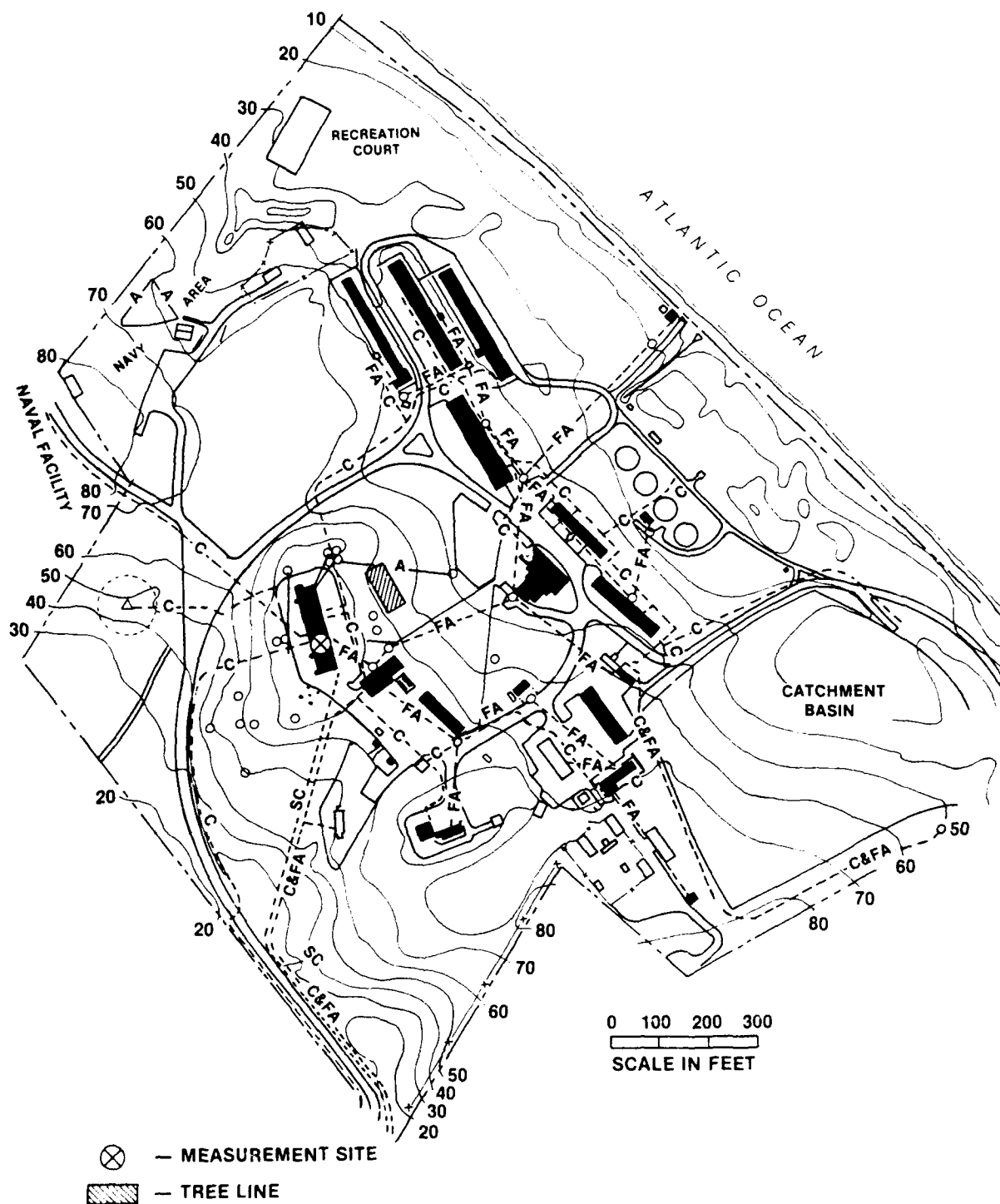


Figure 1. Data Measurement Site

4. Data Storing Unit 2990: This data storage unit accepts the 10-bit binary code generated by the scanning unit through a serial connection. The unit is battery powered and has a capacity of 65,535 data words.

DEPLOYMENT SCHEDULE

The data acquisition system was in place from 27 April 1989 through 30 March 1990, but continuous operation of all sensors was not achieved. The data collection schedule and a synopsis of recorded data are presented as follows:

0935	27 Apr 1989 - 0635	7 Jun 1989 : Avg, Max, Direction
0645	7 Jun 1989 - 1245	20 Jun 1989 : Avg, Max
1635	20 Jun 1989 - 1535	18 Sep 1989 : Avg, Max, Direction
1545	18 Sep 1989 - 1335	3 Oct 1989 : No Data
1345	3 Oct 1989 - 2235	3 Oct 1989 : Avg, Max, Direction
2245	3 Oct 1989 - 1125	6 Nov 1989 : Max, Direction
1135	6 Nov 1989 - 1005	14 Dec 1989 : No Data
1015	14 Dec 1989 - 1145	30 Mar 1990 : Avg, Max, Direction

DATA INTERPRETATION

The raw data base covered a period of 338 days. Of these, there were 252 days of average wind speed samples totalling 35,885 observations and 287 days of wind bearing samples totalling 38,780 observations.

10-MINUTE OBSERVATIONS

The volume of 10-minute observations prevents any significant means for a display of samples. However, the complete set of samples can be used to determine an overall probability distribution of observed wind speeds. No *a priori* knowledge of the probability density function is assumed. Therefore, the distribution function is termed an empirical probability distribution and is determined by $F_X(x') = P[X \leq x']$; $-\infty < x' < \infty$, or the probability that the random variable of average wind speed X takes on a value in the set $(-\infty, x']$, where x' is a particular value of wind speed. This calculation was performed on the 35,885 average wind speed samples with values of x' at 1-knot intervals (figure 2). In particular, it is seen that conditions of 5 knots or less were measured 19 percent of the time, and 15 knots or less 93 percent of the time. The median, or the value of the random variable in the middle of the distribution, is 8.5 knots.

Knowledge of the empirical probability distribution function provides a basis for the computation of a probability density through the well-known integral relationship. The method employed was to model the calculated empirical distribution function as a Chebyshev approximation of order $n = 40$. Once the Chebyshev coefficients are determined for the modeled distribution function, it is straightforward to obtain the Chebyshev coefficients for the derivative of the function. The Chebyshev polynomial is then evaluated for the derivative of the function at 1-knot intervals; the results are shown in figure 3. To provide a continuous function for the initial Chebyshev approximation, the distribution function was first interpolated by a cubic spline. Evaluation of the Chebyshev coefficients revealed that the first 9 terms were sufficient; the remaining 31 were discarded. The probability density reveals a mode (a value of the random variable with the largest probability) of 7 knots.

The calculated probability density is seen to fall between the forms specified by the Gaussian and Rayleigh density functions. A reasonable fit was modeled by a gamma distribution.

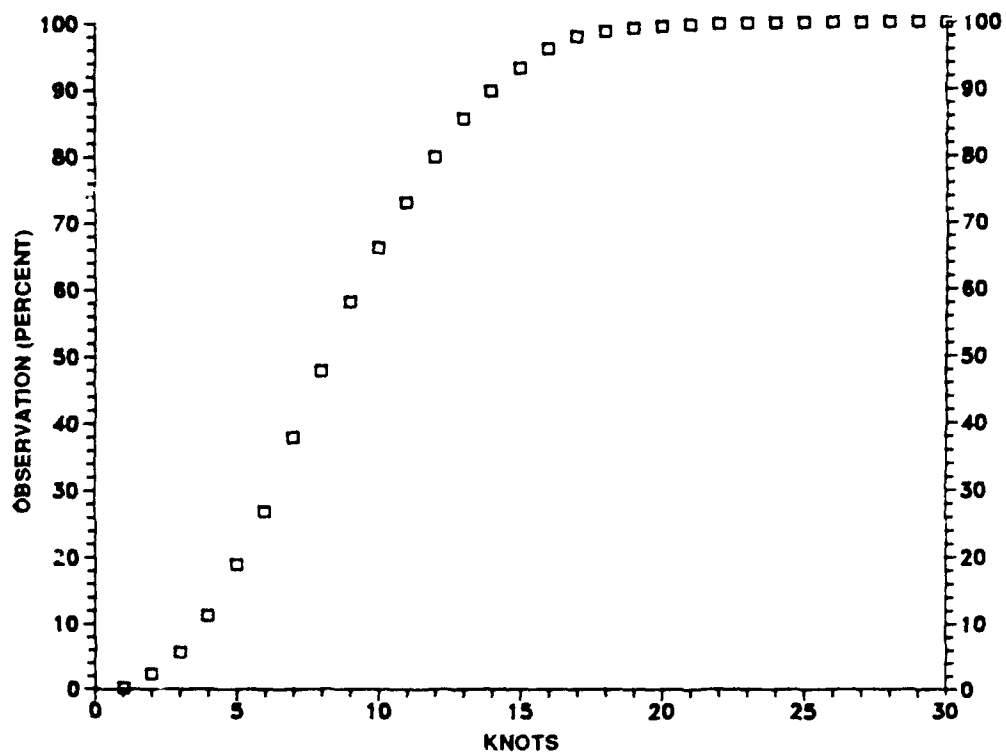


Figure 2. Empirical Distribution Function

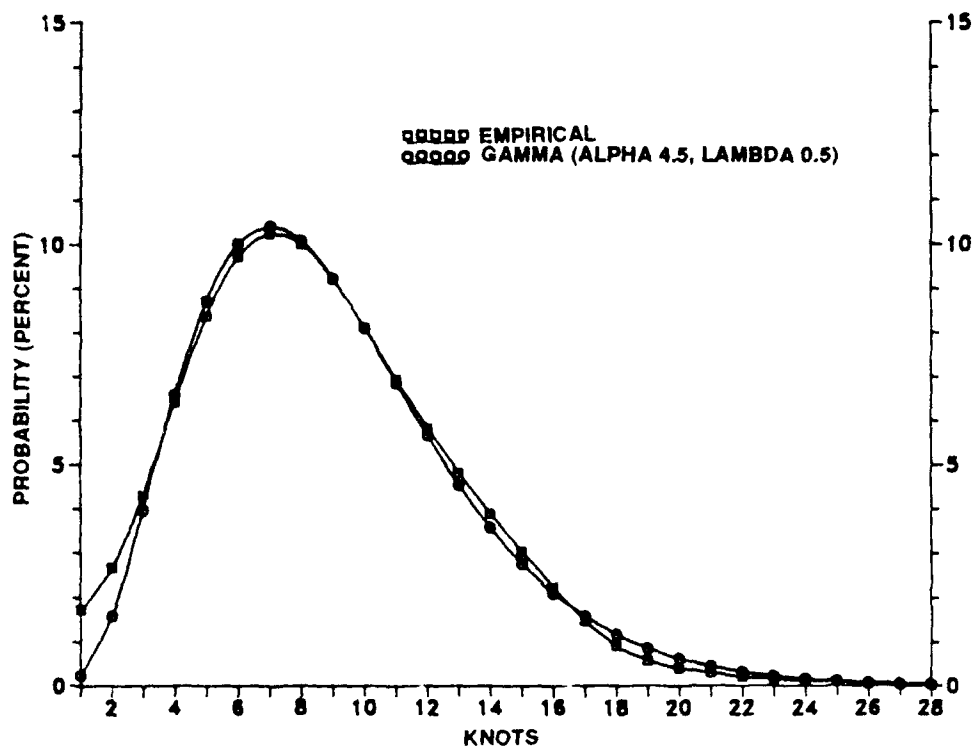


Figure 3. Probability Density Function

$$f_x(x) = \frac{\lambda(\lambda x)^{\alpha-1} e^{-\lambda x}}{\Gamma(\alpha)},$$

with $\alpha = 4.5$ and $\lambda = 0.5$ (figure 3). The modeled gamma distribution is termed "reasonable" in the sense that it was found to minimize a chi-square goodness-of-fit statistic,

$$D^2 = \sum_{k=1}^K \frac{(f_k - F_k)^2}{F_k},$$

for 1-knot intervals from $k = 1$ to $K = 30$ with f_k the observed outcomes in the k^{th} interval and F_k the expected outcomes in the k^{th} interval. The model distribution is not reasonable in the sense that the 1-percent significance criterion for the chi-square hypothesis test was rejected. The first moment of the gamma probability is $E[x] = \alpha/\lambda$, which for the particular case evaluates to 9. The second moment is $E\{[x - E(x)]^2\} = \alpha/\lambda^2 = 18$, and indicates a deviation of 4.3. Note that a gamma density function with $\lambda = 0.5$ and $\alpha = n/2$, where n is a positive integer, is a special case known as the chi-square probability density with n degrees of freedom. A chi-square probability is known to arise from the sum of n mutually independent, squared, normal random variables.

To provide comparisons with the conventional time scales of 1 month, the empirical distribution functions are also calculated for 1-month durations. Figure 4 presents the distribution functions for April through September 1989, and figure 5 shows the results for October 1989 through March 1990. Note that no data were available for November 1989, and only sparse data were available for October 1989.

HOURLY AVERAGED OBSERVATIONS

To reduce the volume of observations to a manageable level, hourly averages are computed from the 10-minute samples. An hourly average is computed from three observations on either side of the hour, i.e., for the 1000 average, the six observations at 0935, 0945, 0955, 1005, 1015, 1025 are averaged. To avoid confusion with a strictly Gaussian probability distribution, the average will be defined as the mean estimator $\bar{x}$, and is computed as

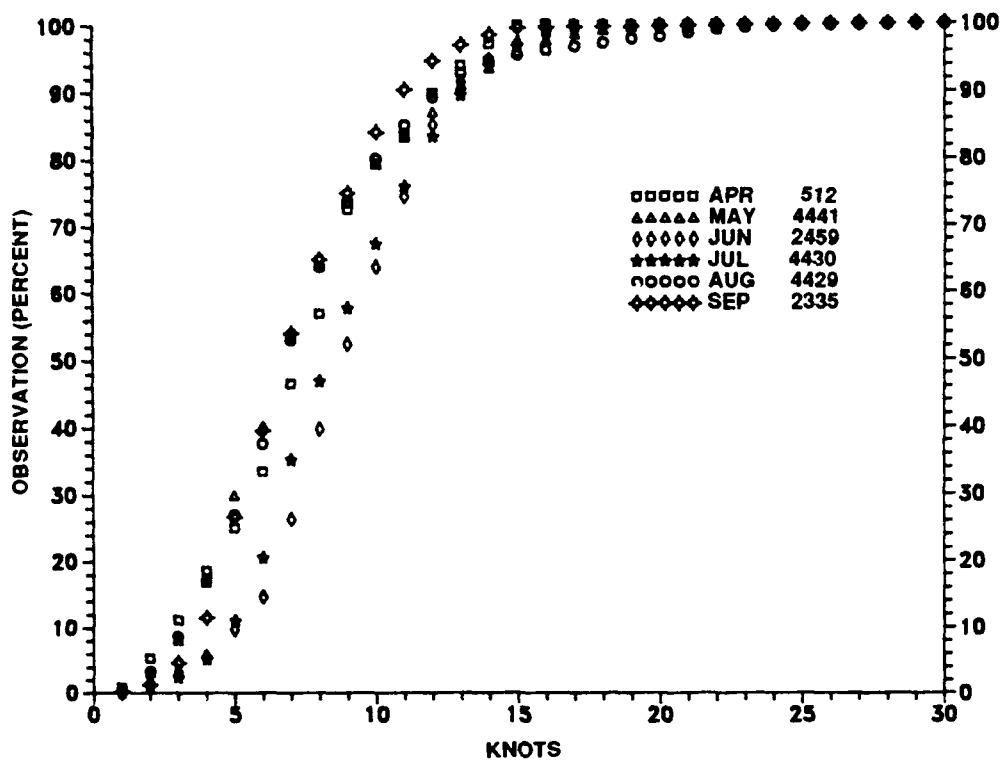


Figure 4. Empirical Distributions for April Through September 1989

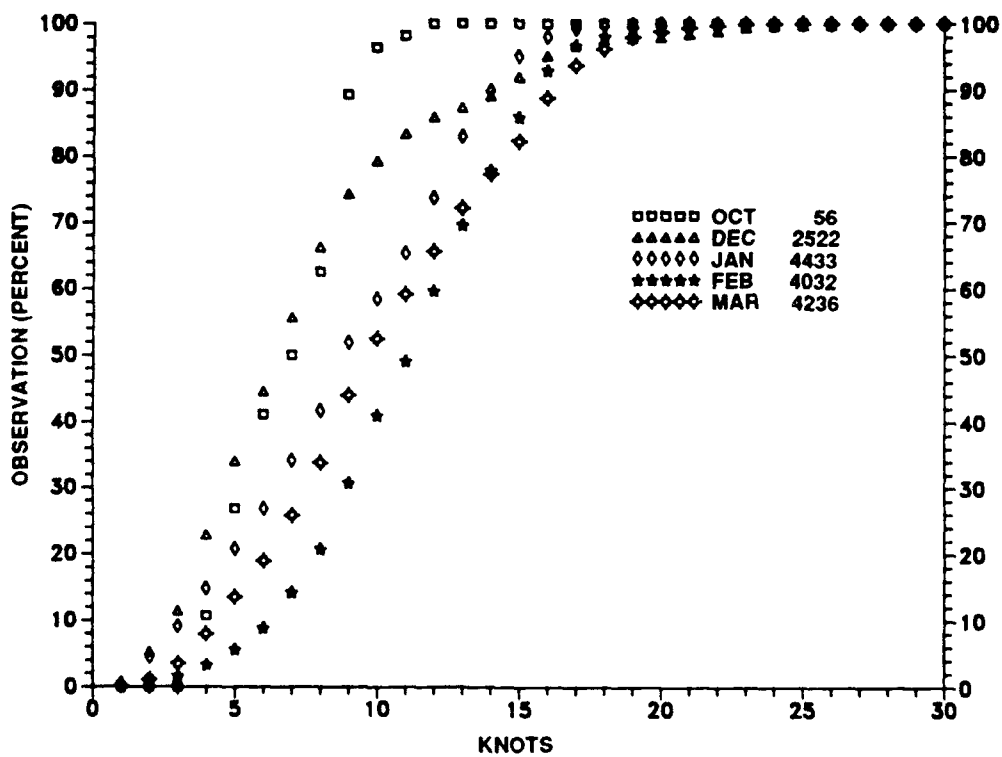


Figure 5. Empirical Distributions for October 1989 Through March 1990

$$\bar{x} = \frac{1}{N-1} \sum_{i=1}^N x_i .$$

This reduces the number of points for wind speed from 35,885 to 5666. Figure 6 shows the entire data base presented as hourly averages, with day 0 corresponding to 27 April 1989. It should be noted that the values shown are averages over 1 hour of raw wind speeds averaged over a 10-minute interval.

An estimator for the sample variance is calculated by

$$\bar{s}^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2 .$$

The square root of the variance estimator corresponding to the mean estimates in figure 6 is presented for the hourly data base in figure 7.

The directional data were vector averaged into hourly points with the same six observations per hour format as the wind speed. The raw bearing was converted to sine and cosine components, the components averaged arithmetically, and then recombined for the directional estimate. A plot of the hourly averaged wind direction is shown in figure 8.

To provide a view of the correlation between the observed wind speeds and bearing, the hourly wind speeds and direction estimates were employed to construct a wind speed versus direction histogram. Figure 9 displays the result.

The amount of data available as hourly averages lends itself to power spectral estimation. The hourly wind speed averages were used to calculate a wind speed power spectrum by standard methods. The data were partitioned into blocks of 256 points, tapered with a Welch window, and processed with a 50-percent overlap. This allowed for 23 averages to be used in the power spectral estimate. The result is shown in figure 10. For convenience, several frequencies and corresponding temporal periods are listed

$f \text{ (Hz} \times 10^{-6})$	$T \text{ (hour)}$
23	12.0
40	6.9
50	5.5
90	3.1

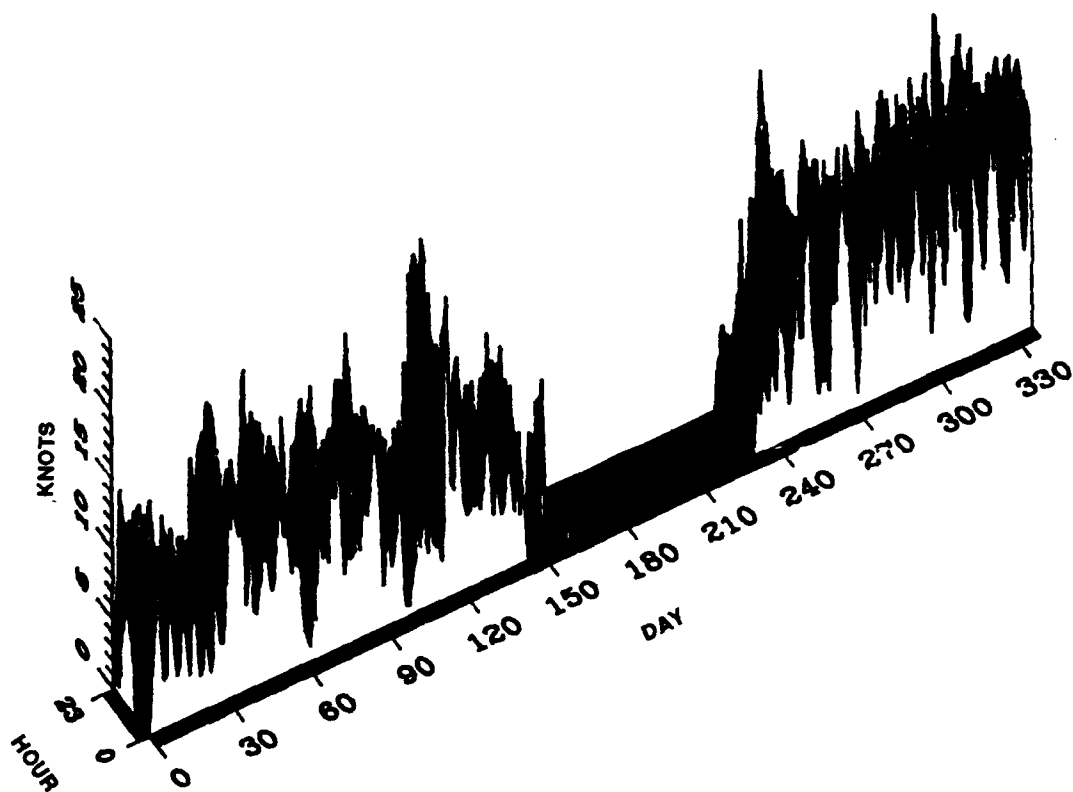


Figure 6. Eleuthera Hourly Wind Speed

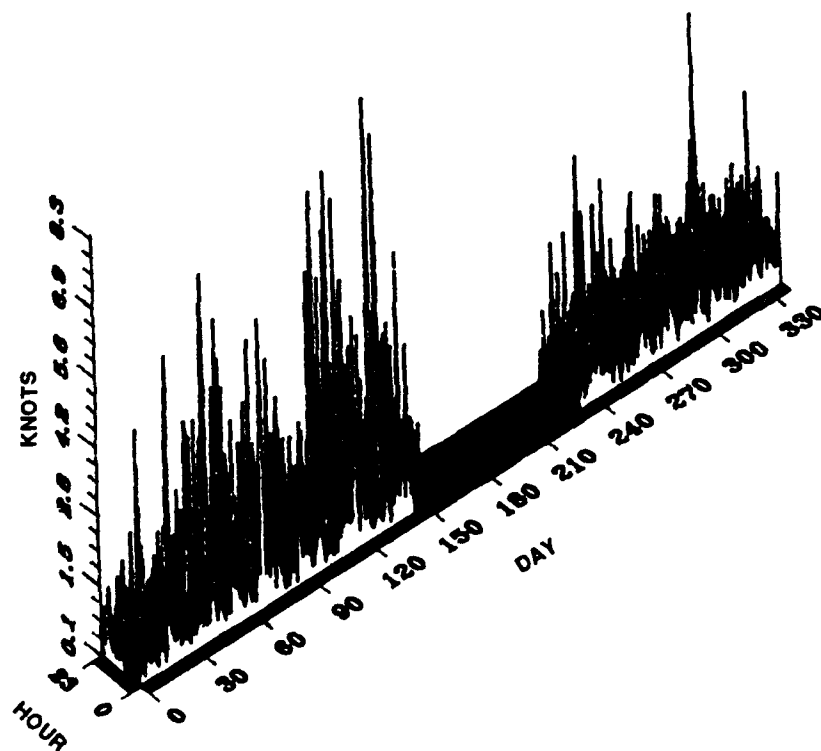


Figure 7. Eleuthera Hourly Wind Deviation

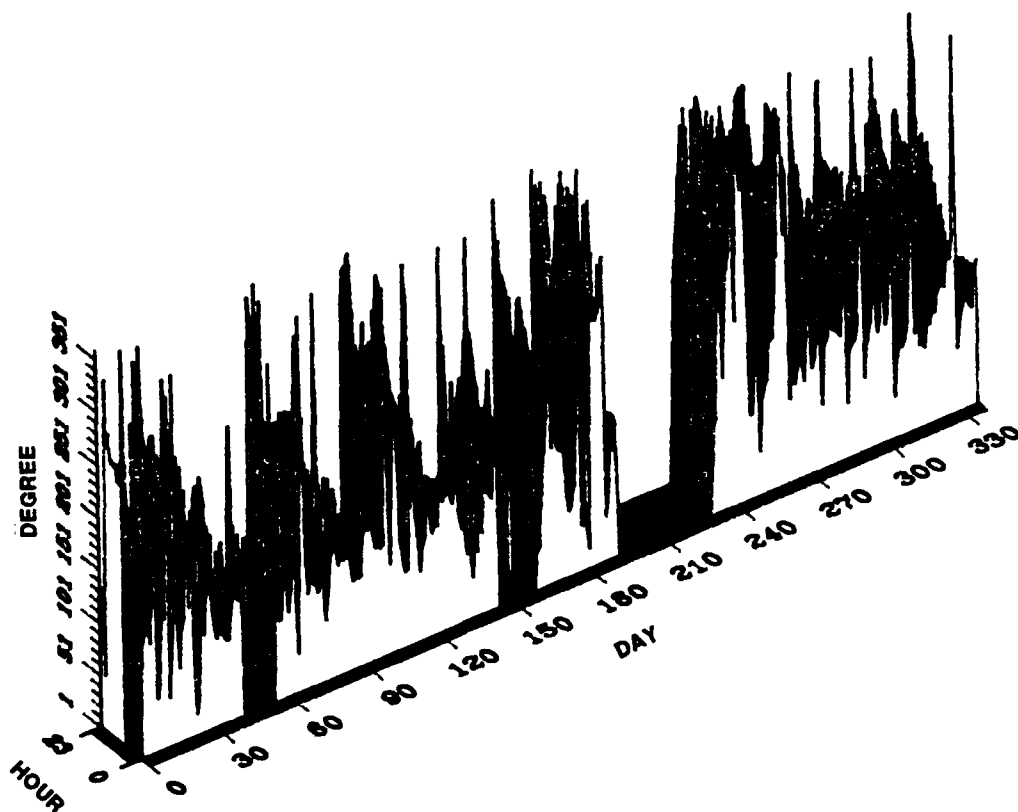


Figure 8. Eleuthera Hourly Wind Direction

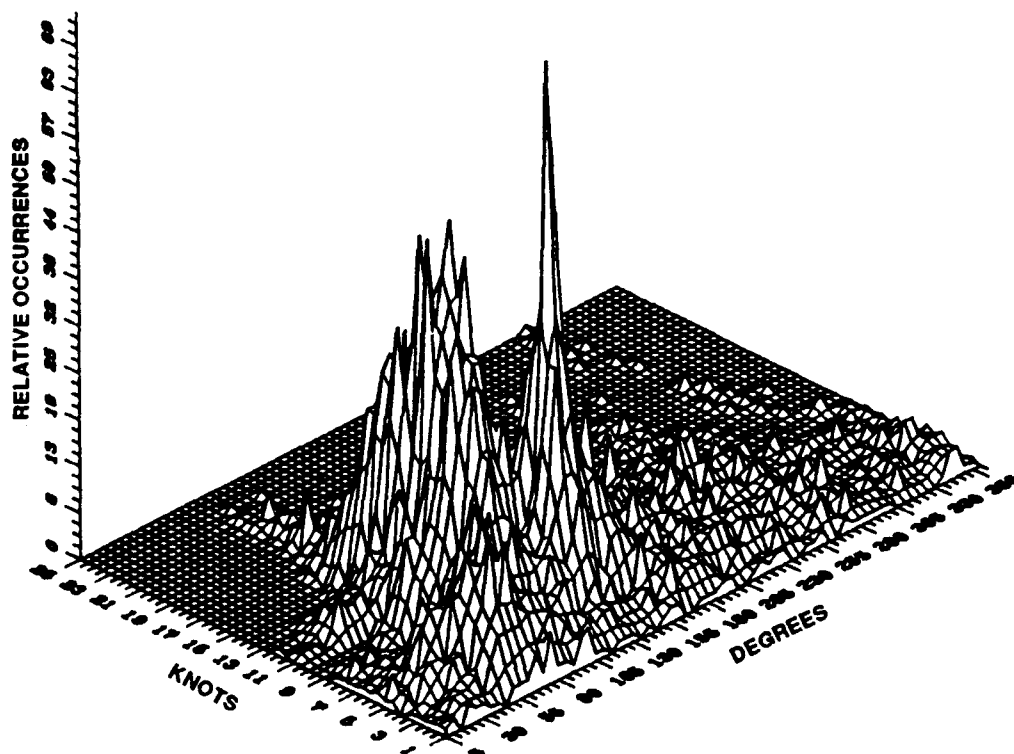


Figure 9. Eleuthera Wind Speed vs Direction

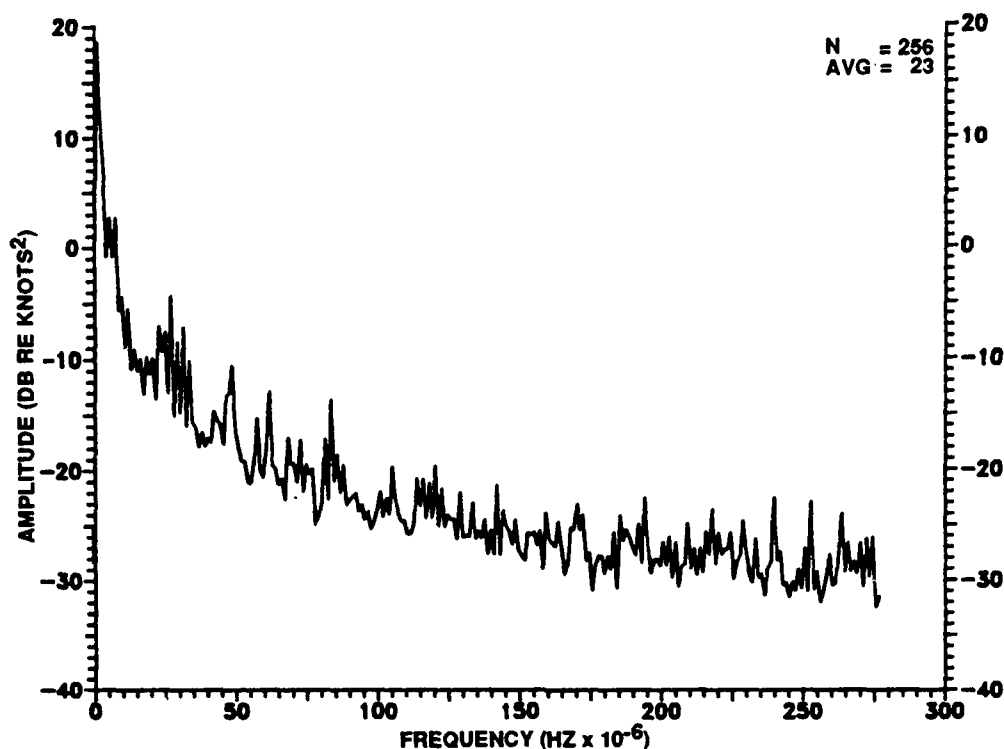


Figure 10. Hourly Average Power Spectrum

A broad contribution of spectral power is seen in the band from 23 to 35×10^{-6} Hz, corresponding to periodic processes with characteristic times of 8 to 12 hours. Additional spectral peaks are observed for frequencies of 44, 50, 63, and 84×10^{-6} and respective periods of 6.3, 5.6, 4.4, and 3.3 hours.

DAILY AVERAGED OBSERVATIONS

To further condense the raw data into a manageable format, the hourly averages were averaged into daily time frames. The data for a particular day are the hourly observations from that day, averaged together with the same mean estimator as for the hourly data. Figure 11 is the resulting sample mean values from each day. Note that the additional averaging has diminished the peak levels.

The corresponding sample variance estimator for the daily averages was also computed. Figure 12 shows the square root of the daily sample variance.

The daily averaged time series was also employed for power spectral estimates. The data were partitioned into blocks of 64 points, tapered by a

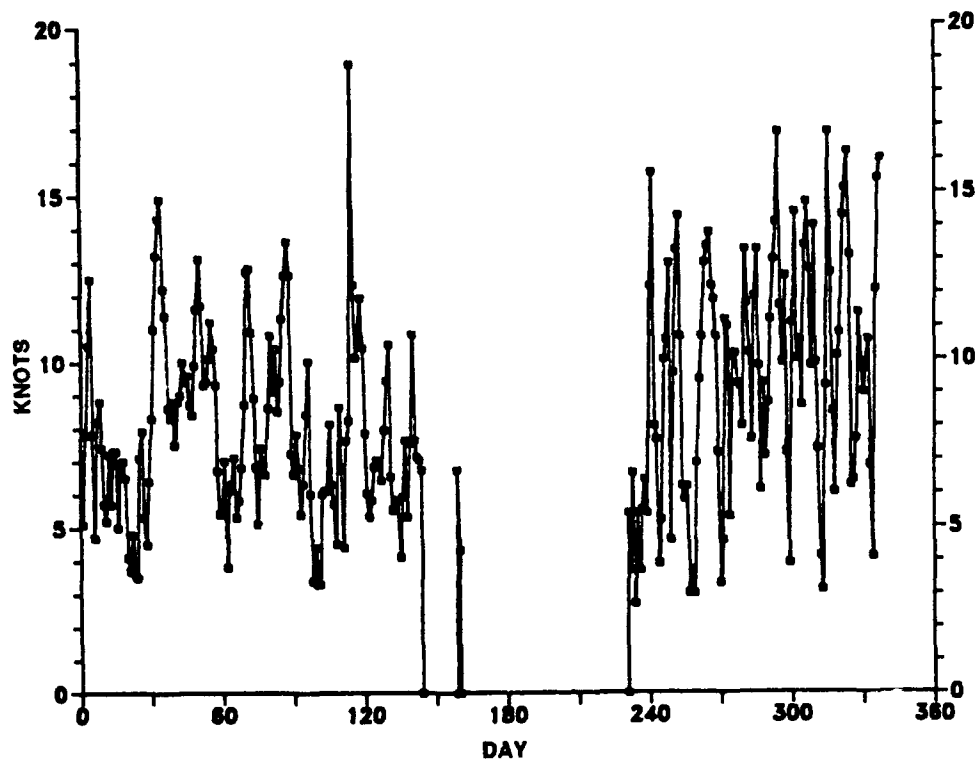


Figure 11. Daily Average Wind Speed

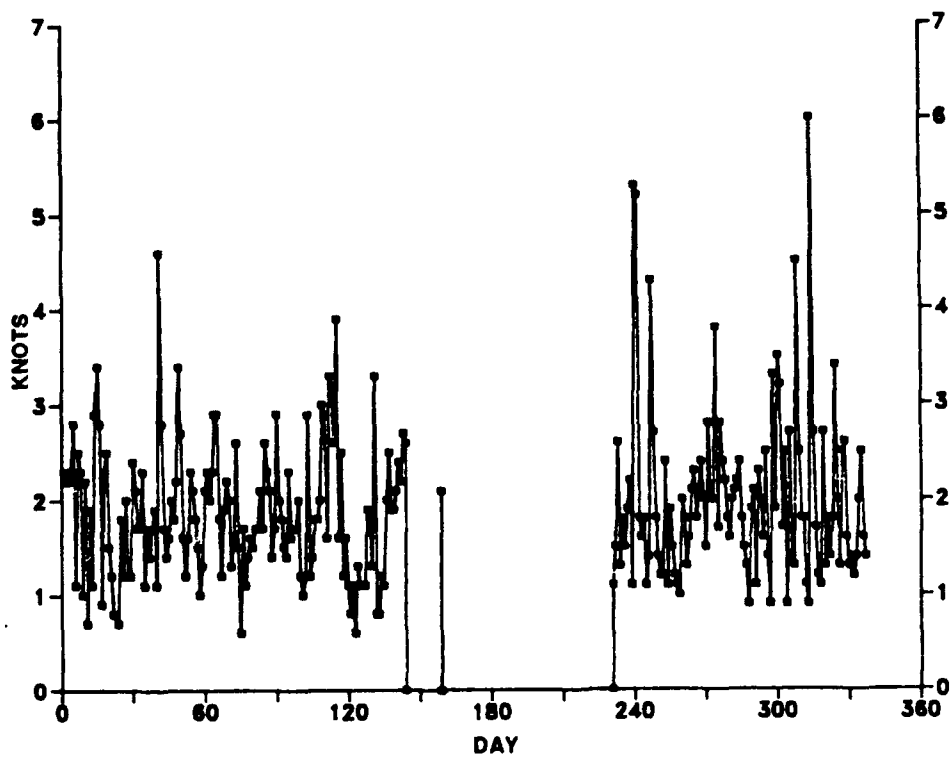


Figure 12. Daily Sample Deviation

Welch window, and processed with a 50-percent overlap; the limited amount of data allowed for only four averages. The resulting spectral estimate is shown in figure 13. Strong spectral peaks are shown at frequencies of 20, 34.5, 57, 78, and 82×10^{-7} Hz, with respective periods of 5.65, 3.35, 2.03, 1.48, and 1.41 days. The positive spectral slope for frequencies higher than 90×10^{-7} is attributed to the emergence of a diurnal cycle; the peak at 110×10^{-7} indicates a periodic component of 25.25 hours.

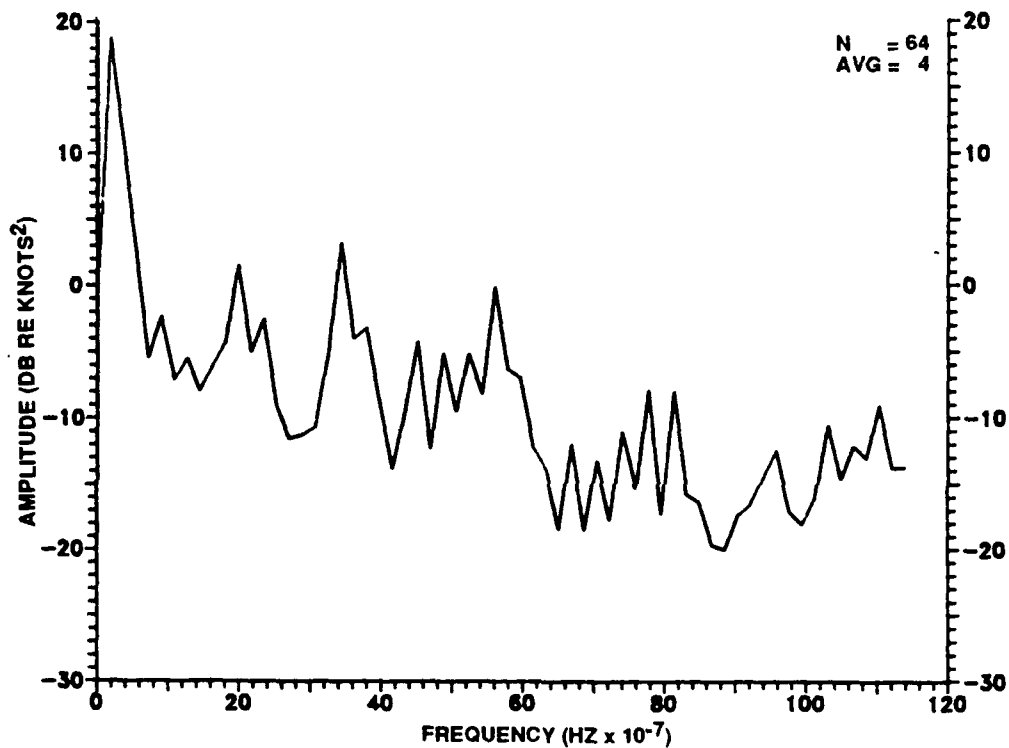


Figure 13. Daily Average Power Spectrum

MONTHLY AVERAGED OBSERVATIONS

To provide a summary of observations compatible with previous environmental observations at AUTECH (reference 1), this section presents monthly histograms and wind roses for the data base. Figure 14 through 46 are the monthly histograms of wind speed and direction and wind roses.

The calculated Gaussian mean, standard deviation, and number of observations for each month are compiled as follows in table 1 for convenience:

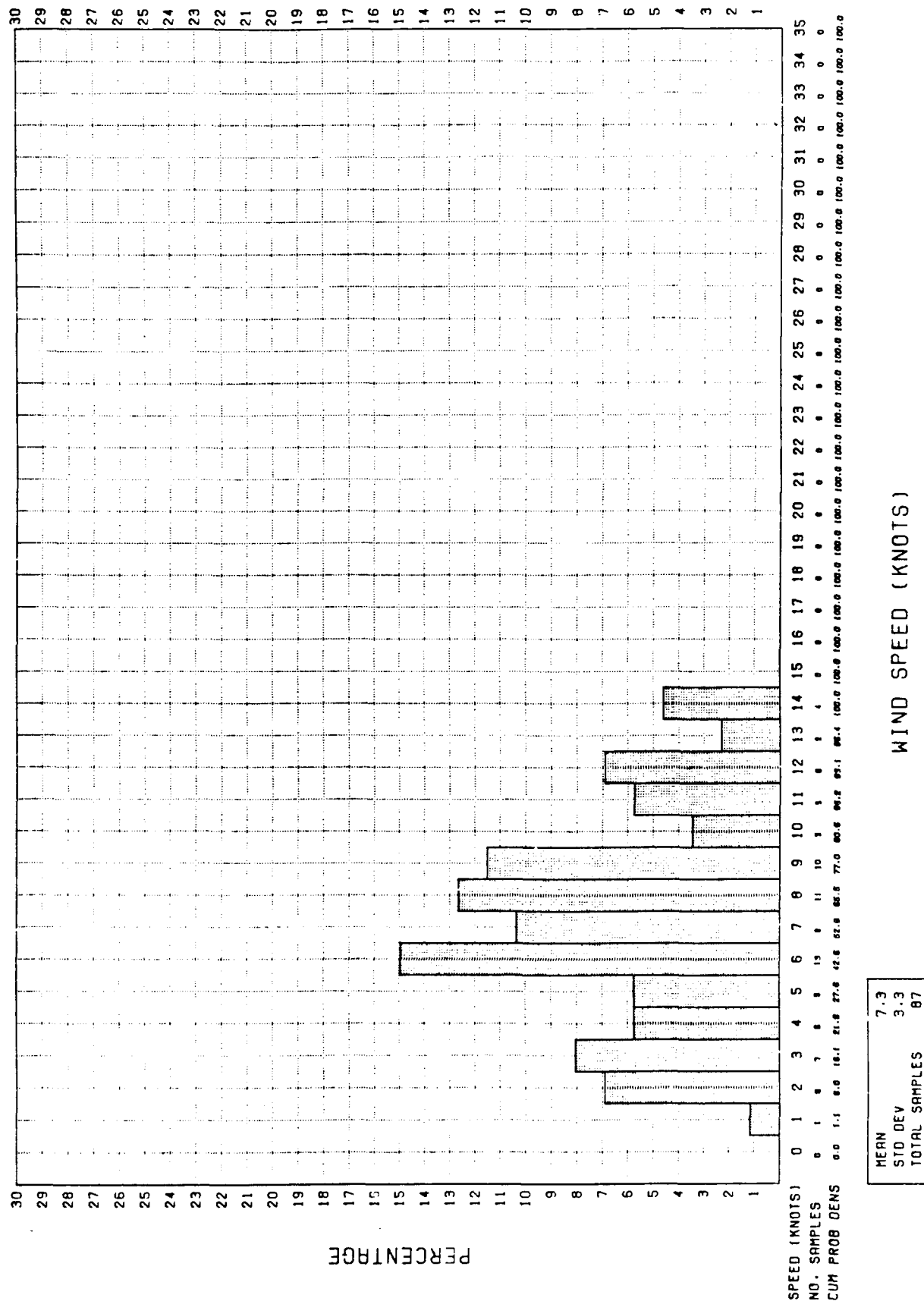


Figure 14. Wind Speed Histogram for April 1989

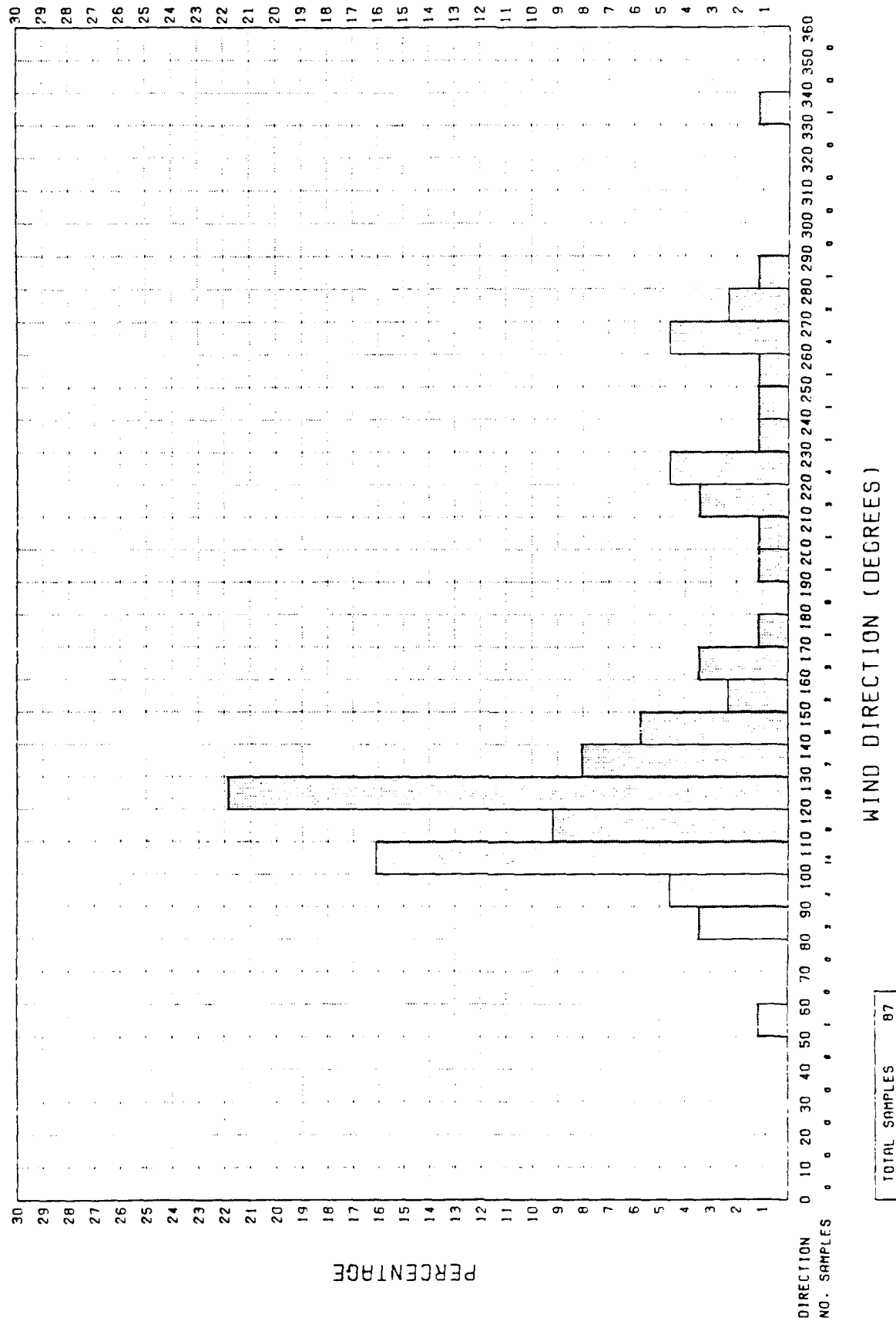
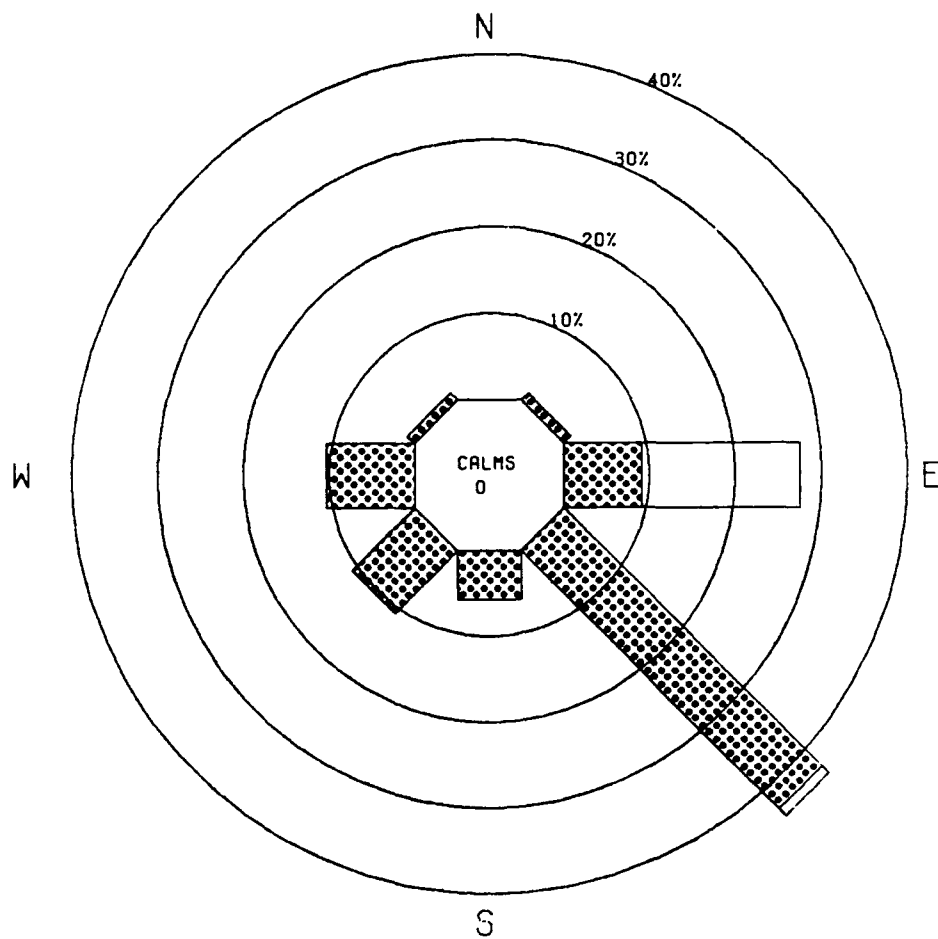


Figure 15. Wind Direction Histogram for April 1989



NUMBER OF OBSERVATIONS -- 87
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

PERCENTAGE OF OBSERVATIONS	WHICH AT SPEEDS ARE OF
	01-10 KNOTS
	11-16 KNOTS
	17-27 KNOTS
	>27 KNOTS

Figure 16. Wind Rose for April 1989

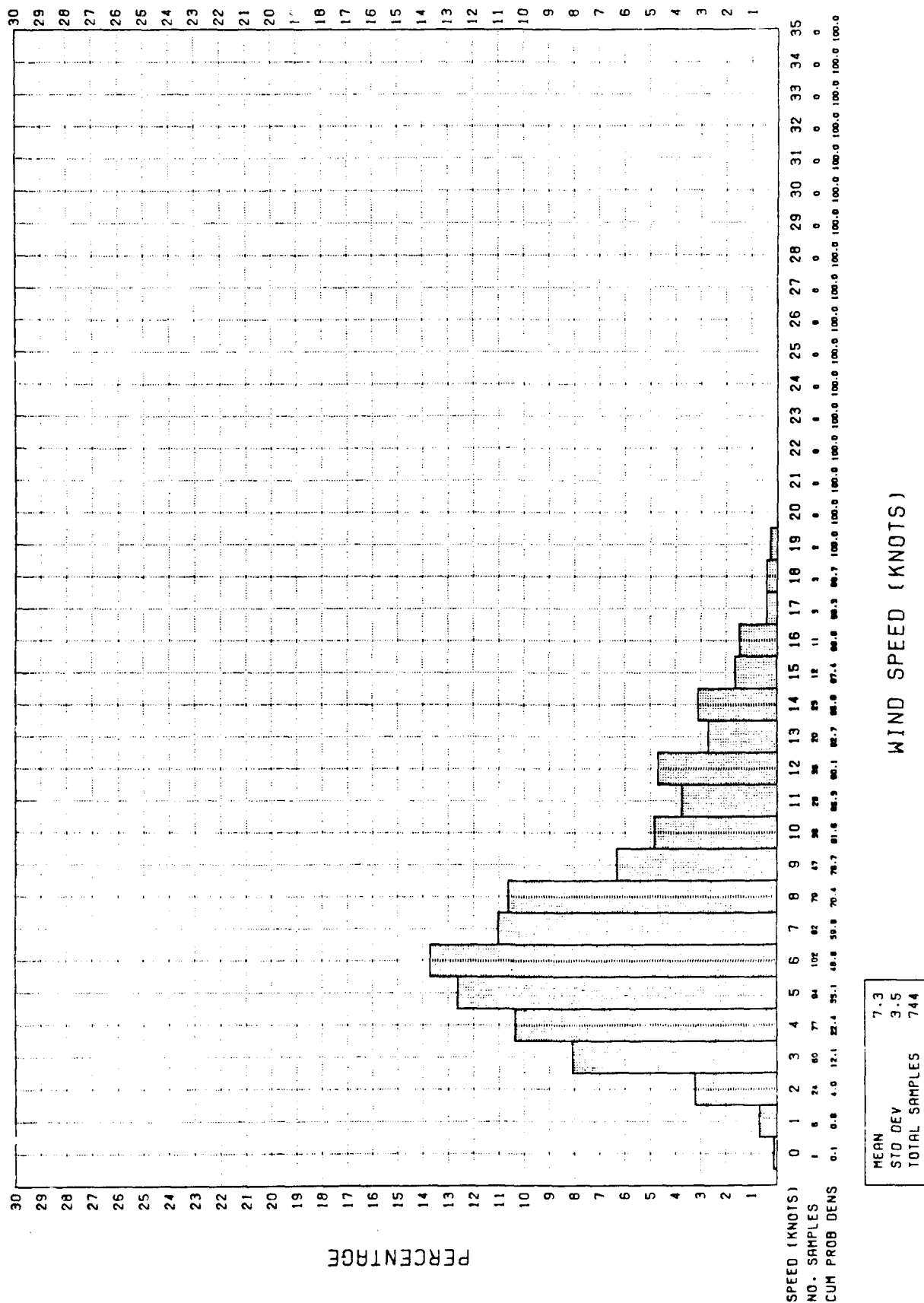


Figure 17. Wind Speed Histogram for May 1989

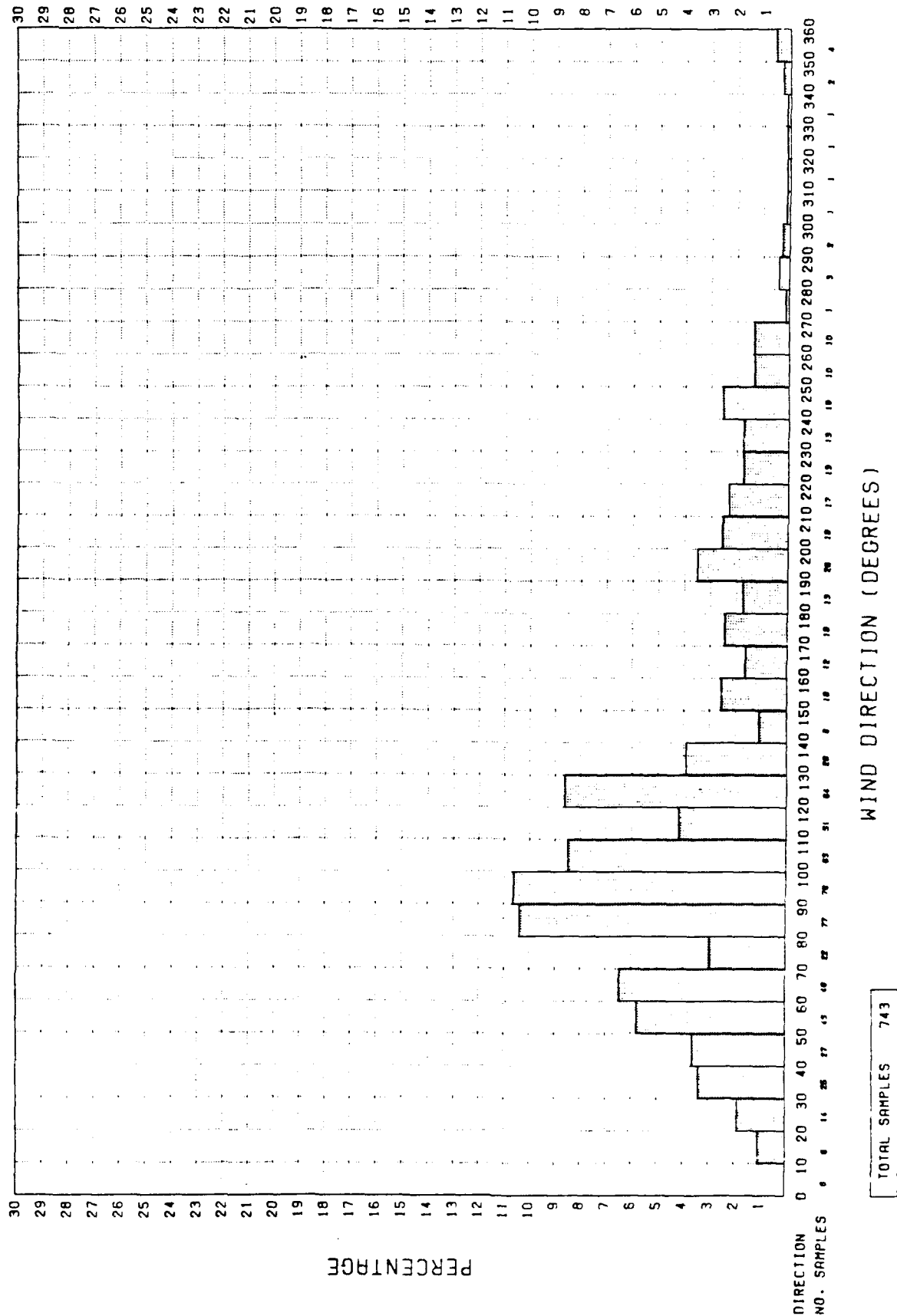
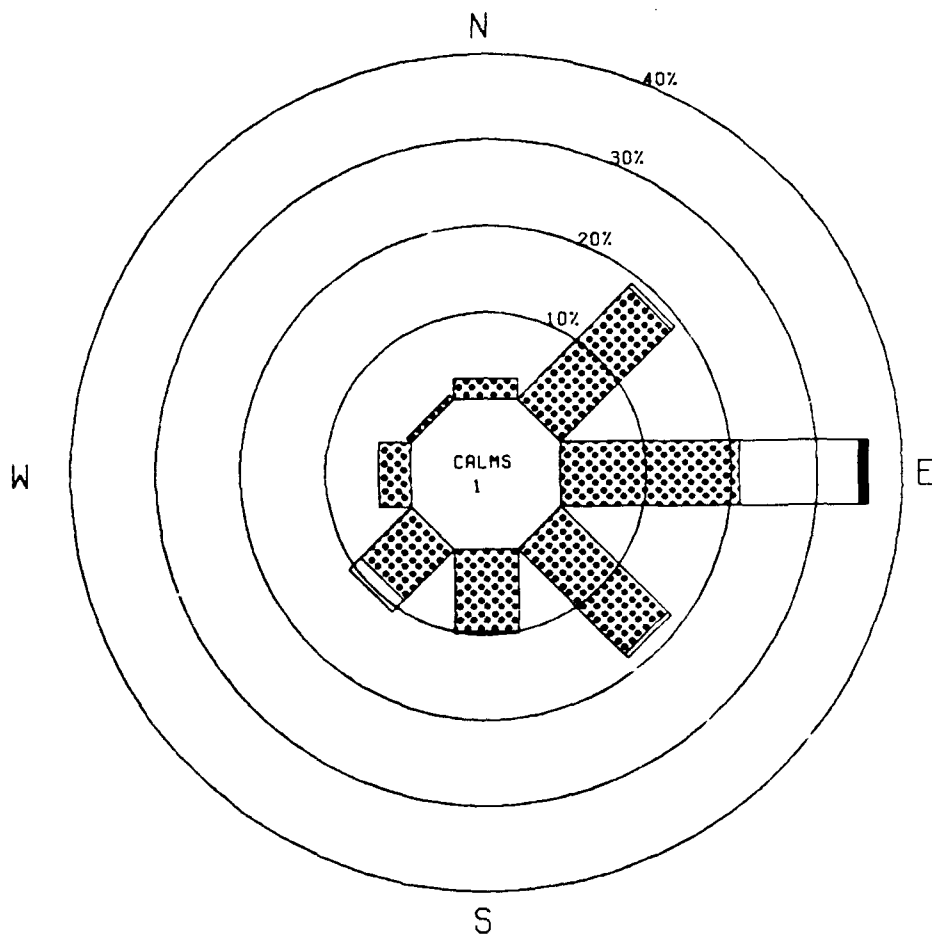


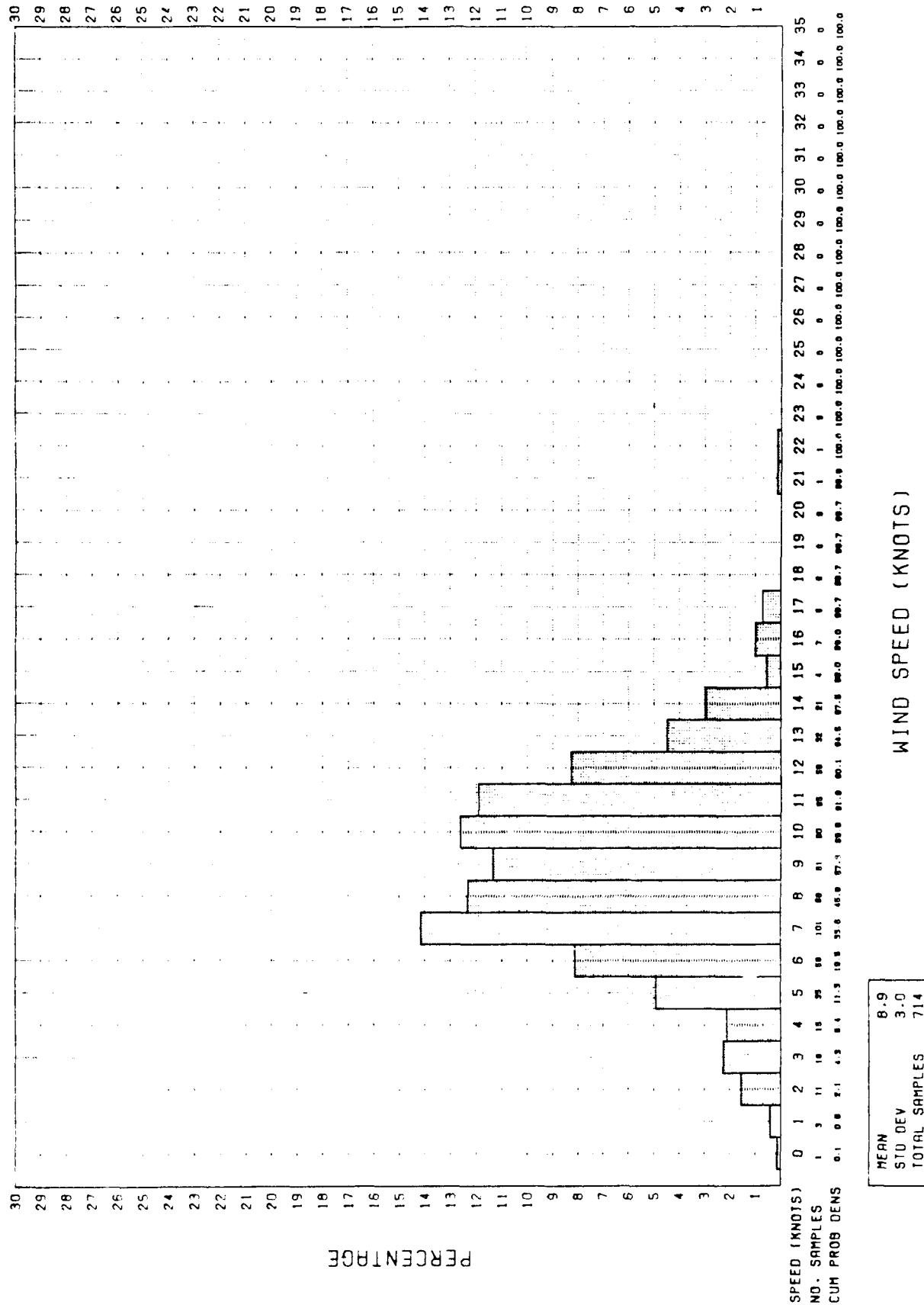
Figure 18. Wind Direction Histogram for May 1989



NUMBER OF OBSERVATIONS -- 744
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

PERCENTAGE OF OBSERVATIONS	WHICH ARE	AT SPEEDS OF
		01-10 KNOTS
		11-16 KNOTS
		17-27 KNOTS
		>27 KNOTS

Figure 19. Wind Rose for May 1989



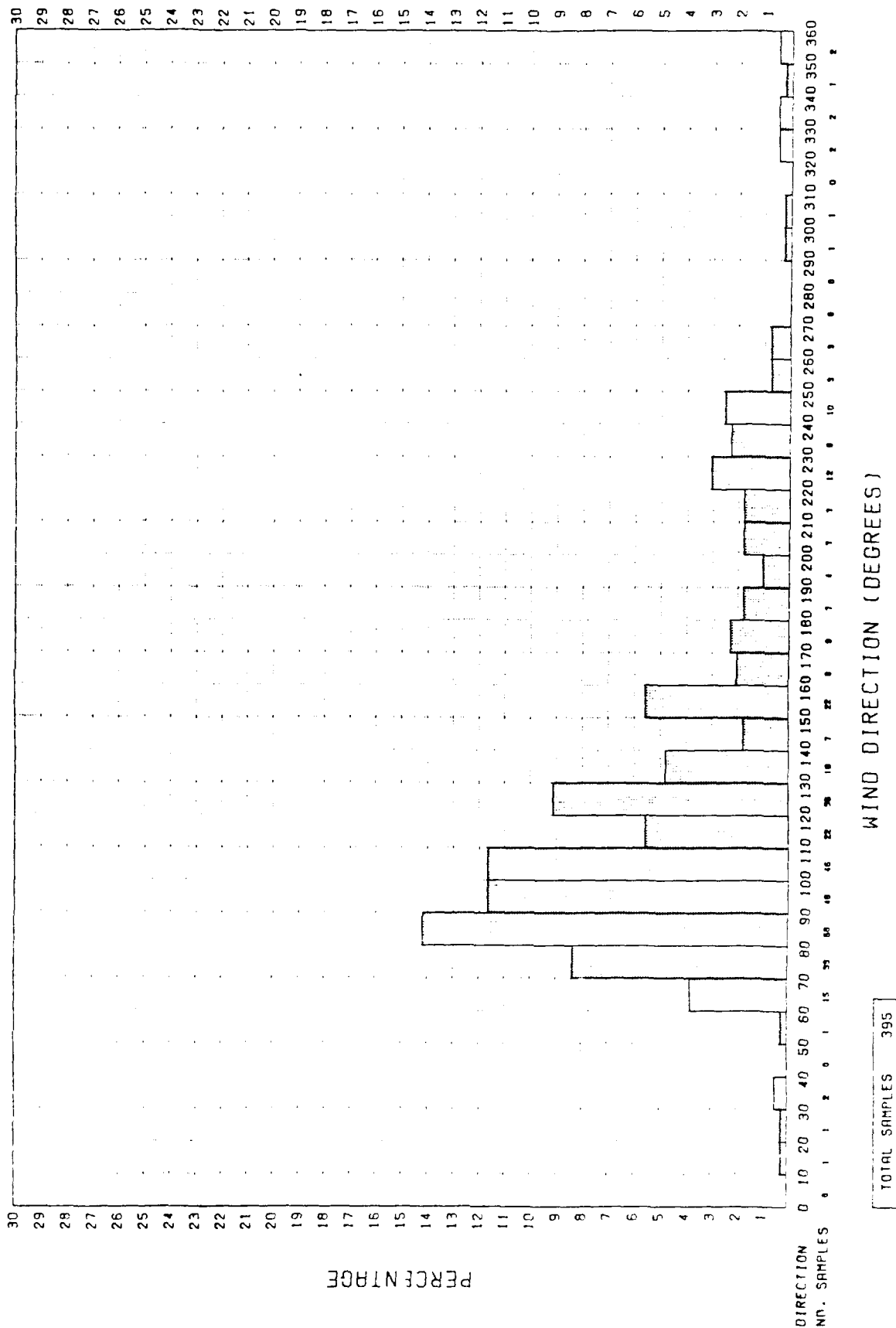
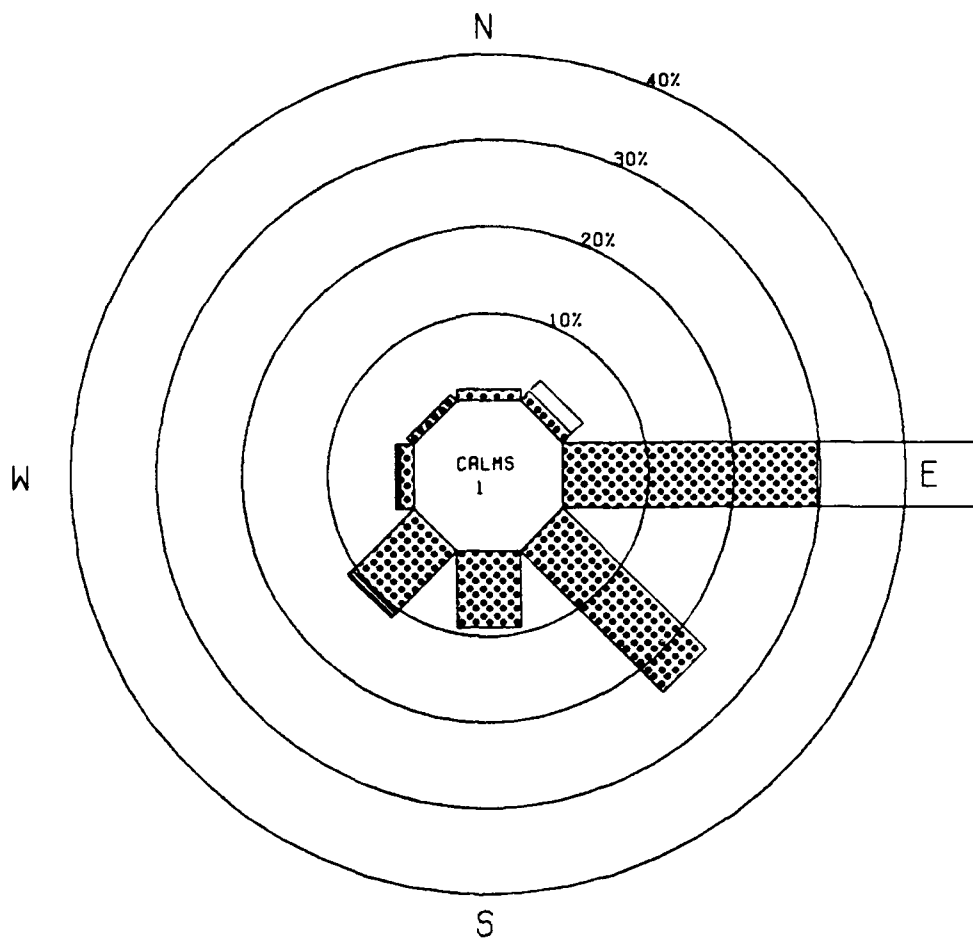


Figure 21. Wind Direction Histogram for June 1989



NUMBER OF OBSERVATIONS -- 396
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

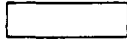
PERCENTAGE OF OBSERVATIONS	WHICH ARE	AT SPEEDS OF
		01-10 KNOTS
		11-16 KNOTS
		17-27 KNOTS
		>27 KNOTS

Figure 22. Wind Rose for June 1989

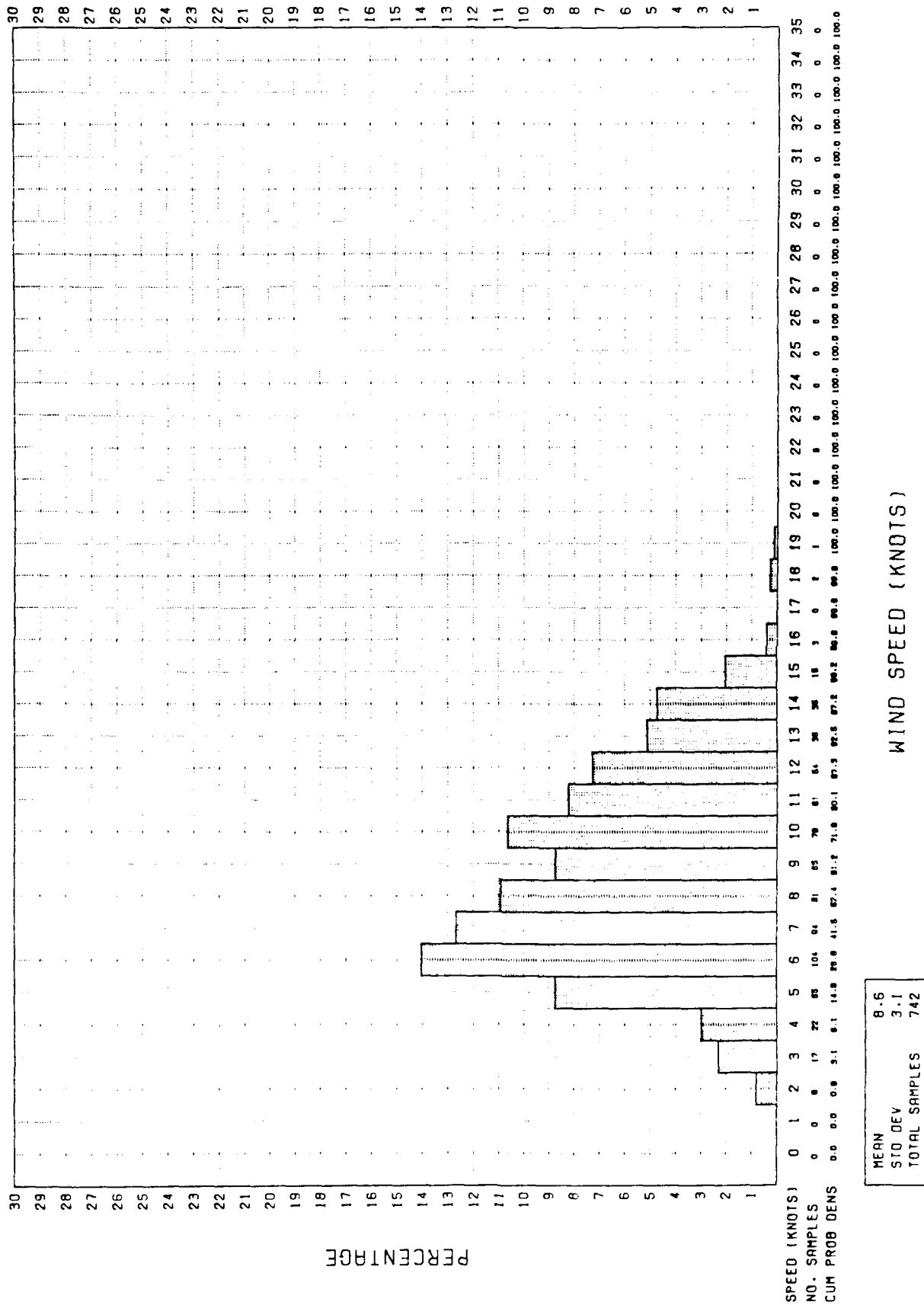


Figure 23. Wind Speed Histogram for July 1989

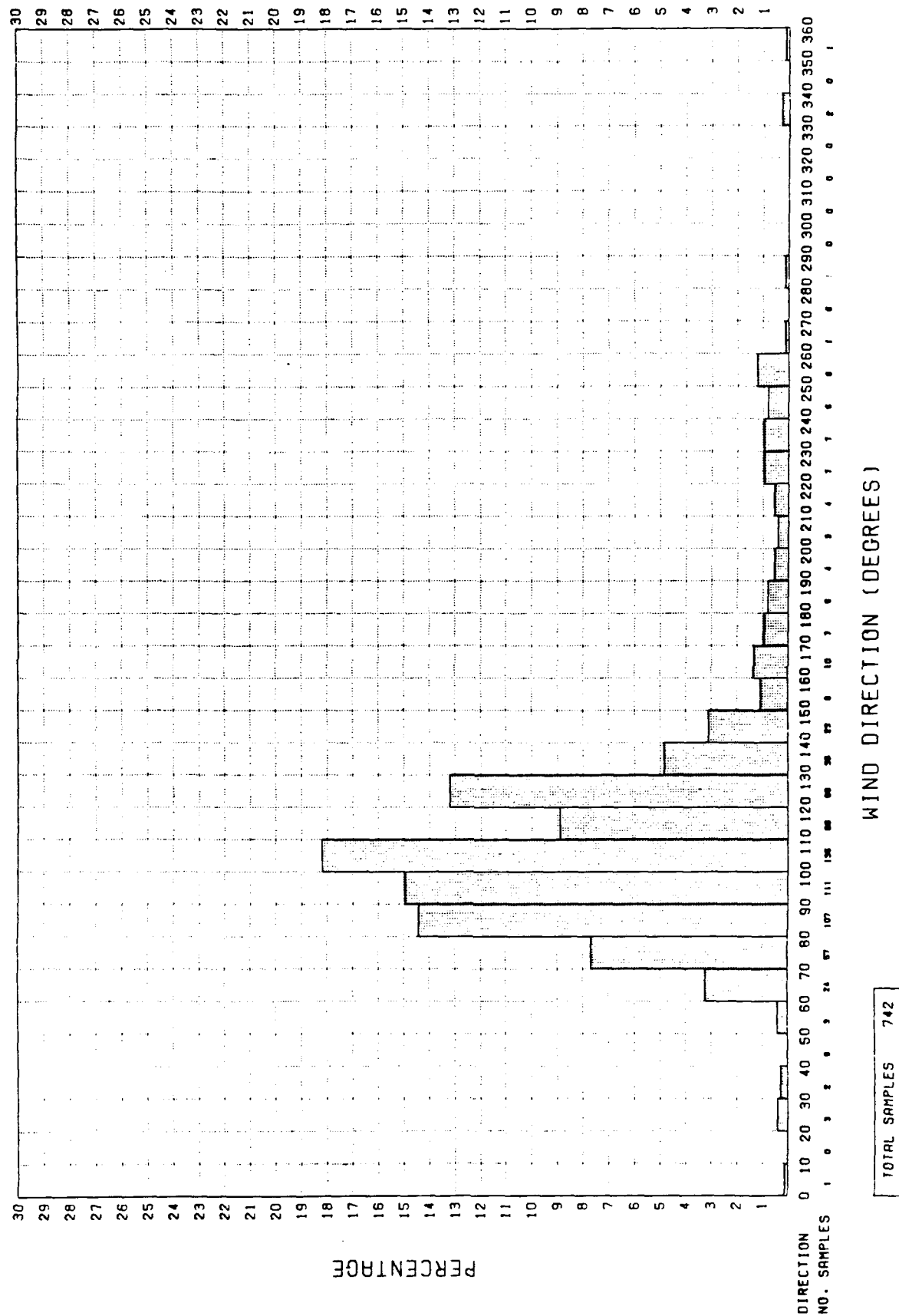
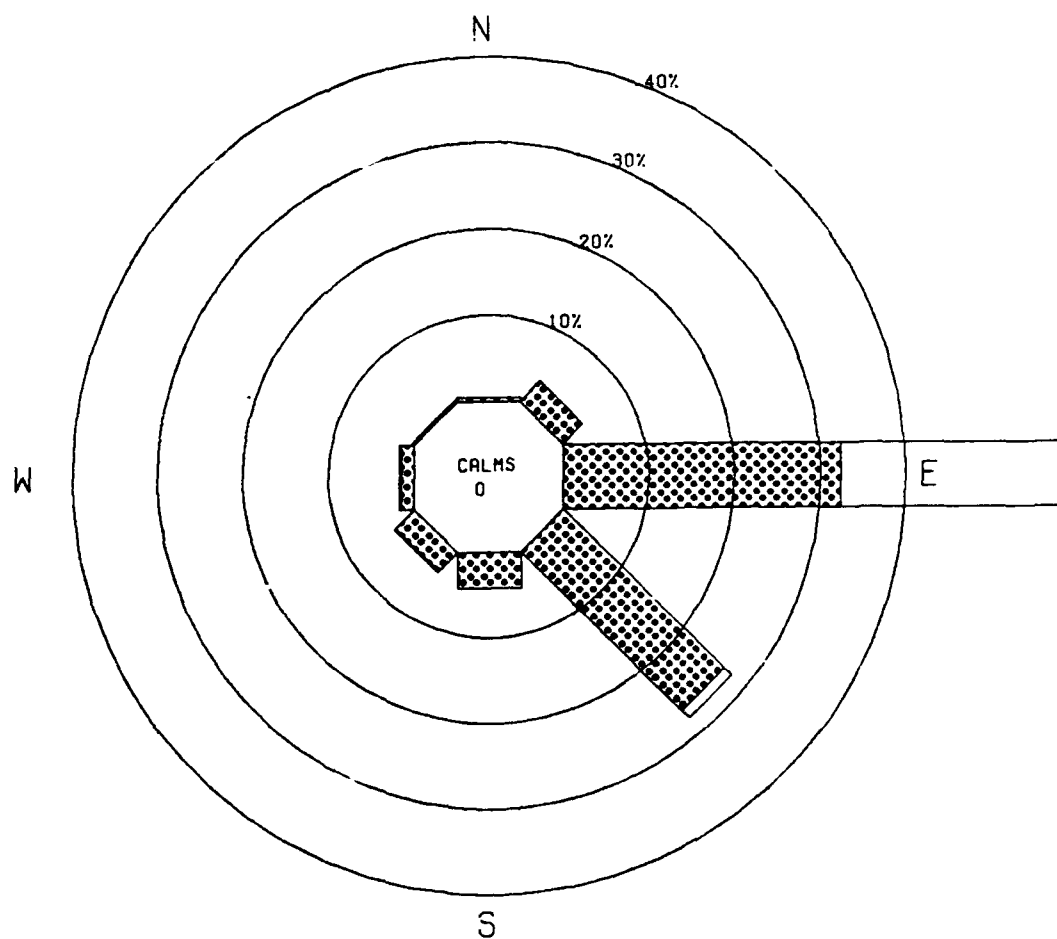


Figure 24. Wind Direction Histogram for July 1989



NUMBER OF OBSERVATIONS -- 742
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

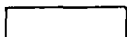
PERCENTAGE OF OBSERVATIONS	WHICH ARE	AT SPEEDS OF
		01-10 KNOTS
		11-16 KNOTS
		17-27 KNOTS
		>27 KNOTS

Figure 25. Wind Rose for July 1989

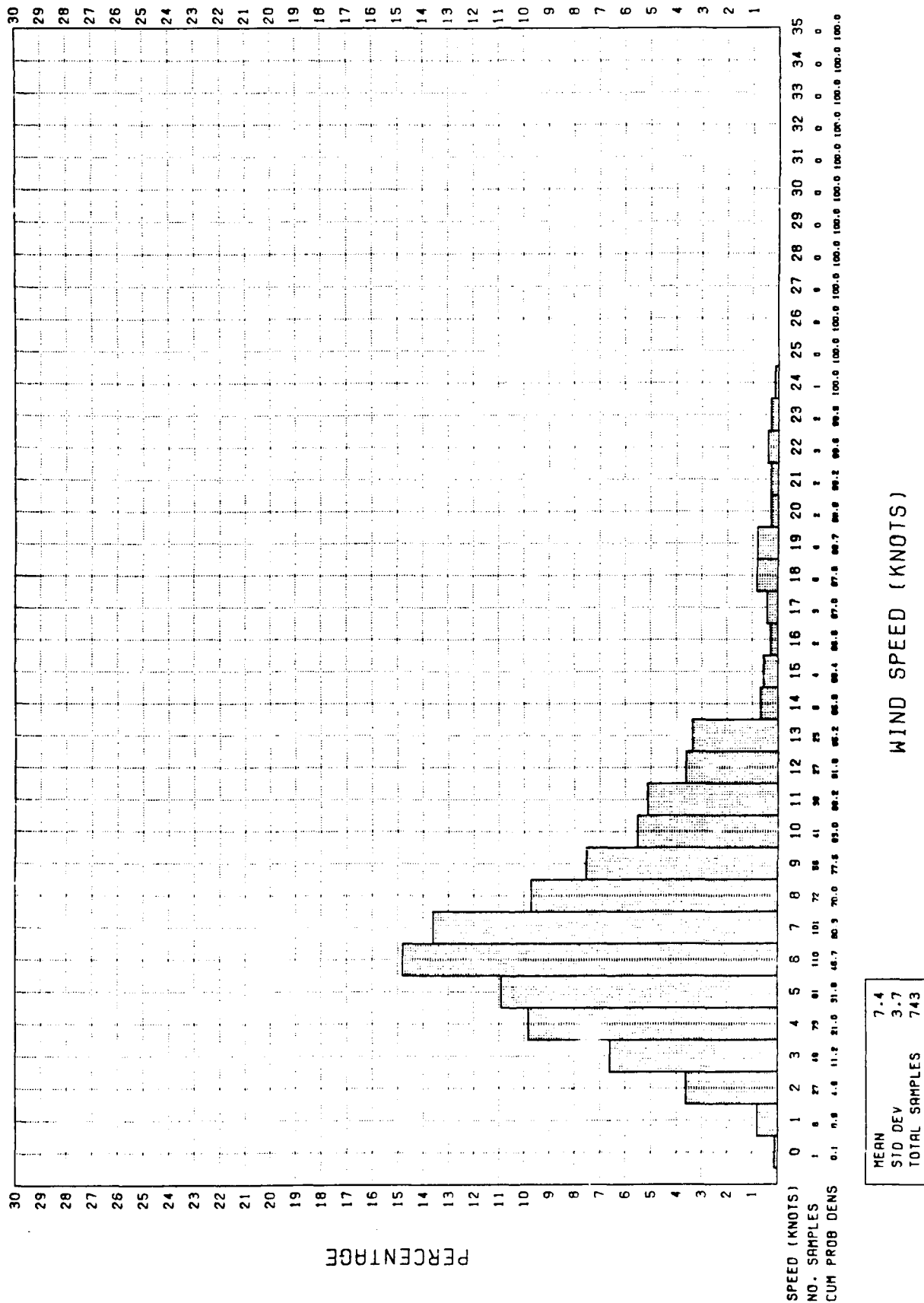


Figure 26. Wind Speed Histogram for August 1989

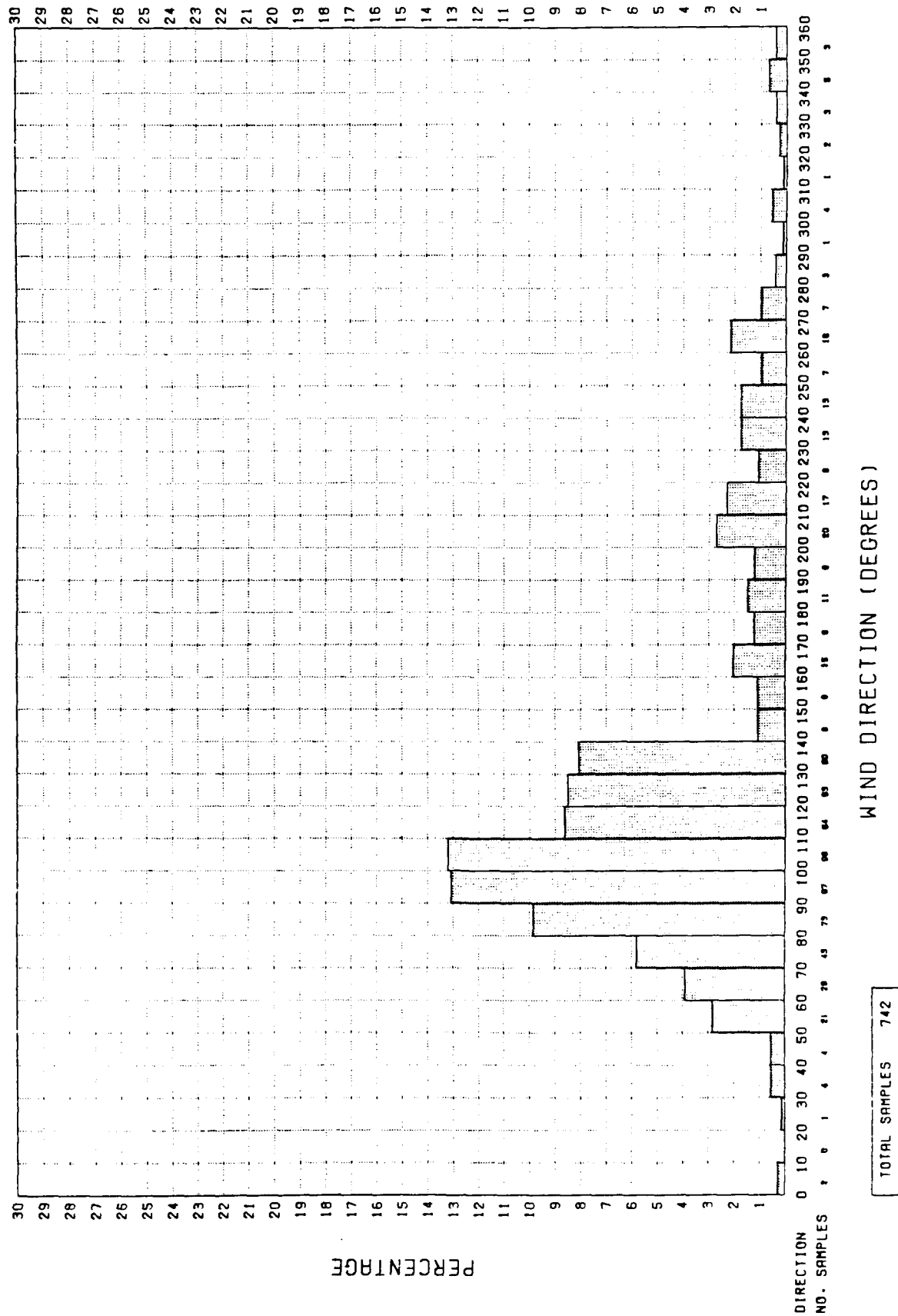
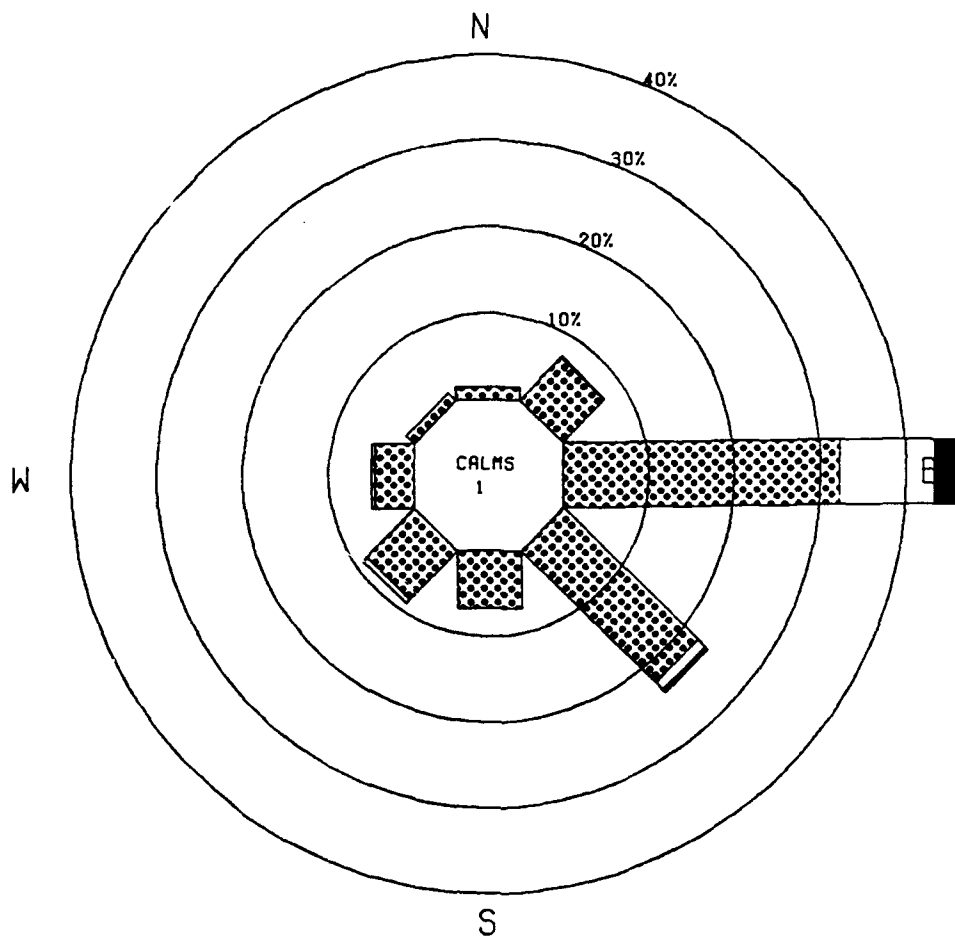


Figure 27. Wind Direction Histogram for August 1989



NUMBER OF OBSERVATIONS -- 743
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

PERCENTAGE OF OBSERVATIONS	WHICH ARE	AT SPEEDS OF
		01-10 KNOTS
		11-16 KNOTS
		17-27 KNOTS
		>27 KNOTS

Figure 28. Wind Rose for August 1989

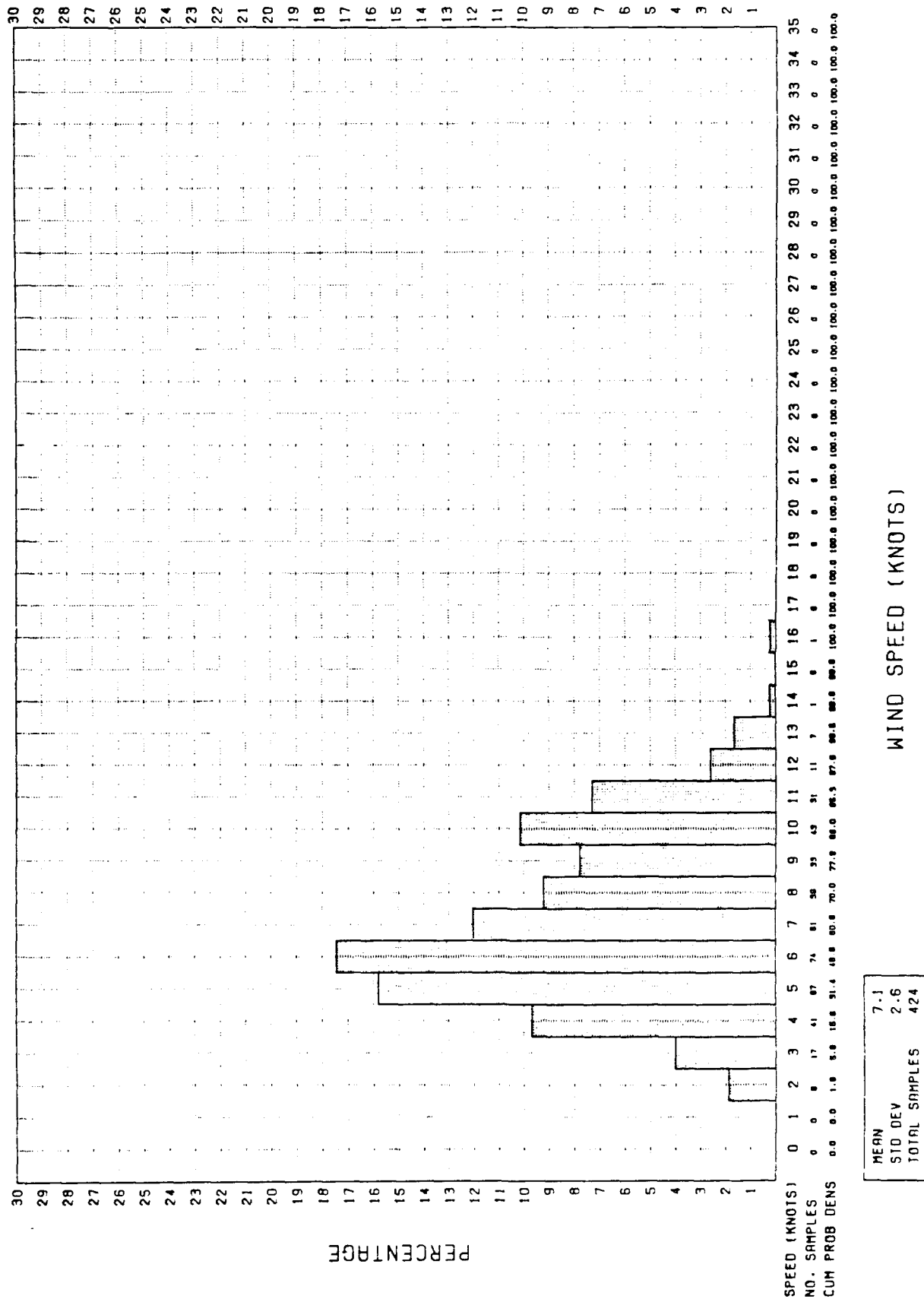


Figure 29. Wind Speed Histogram for September 1989

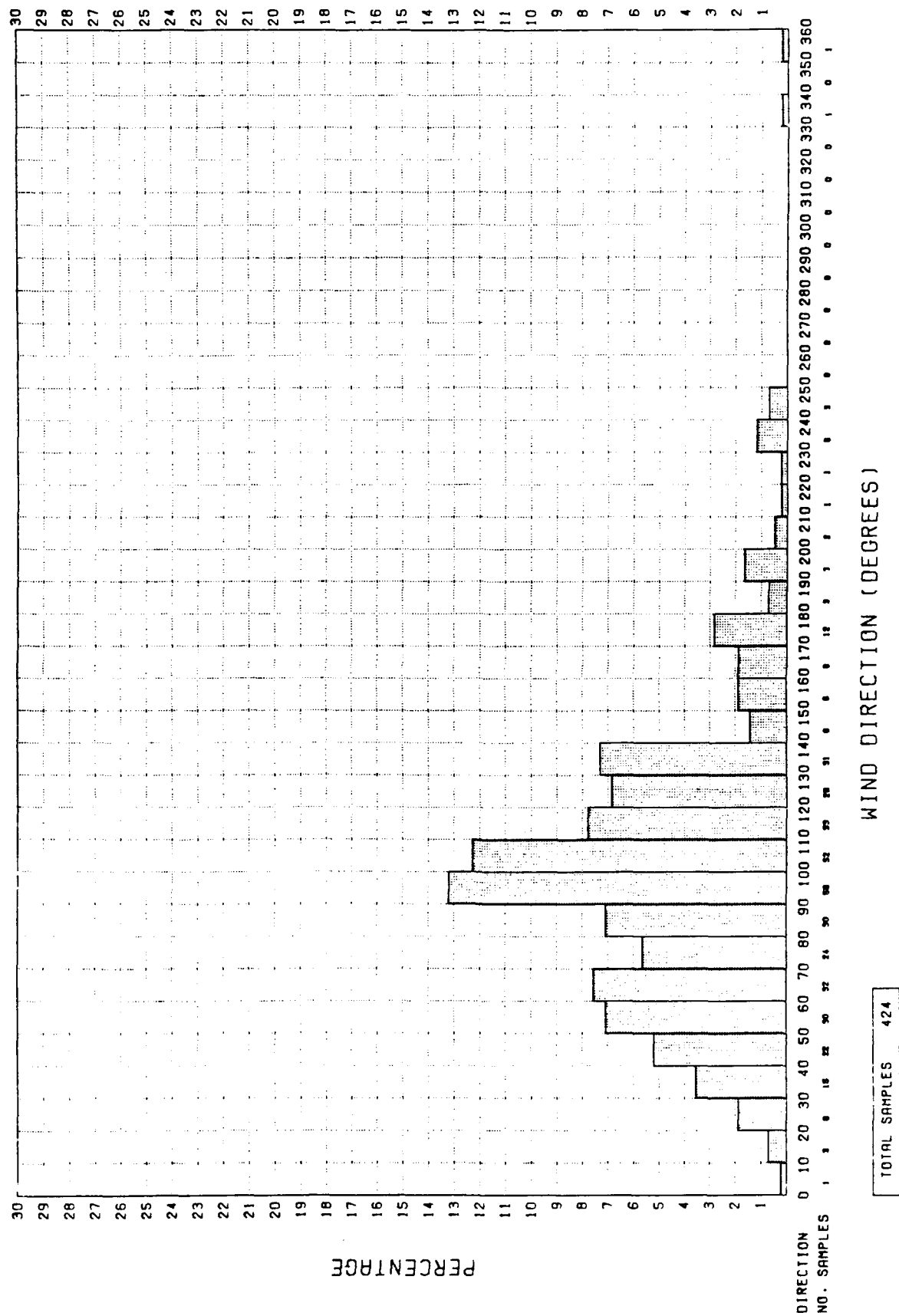
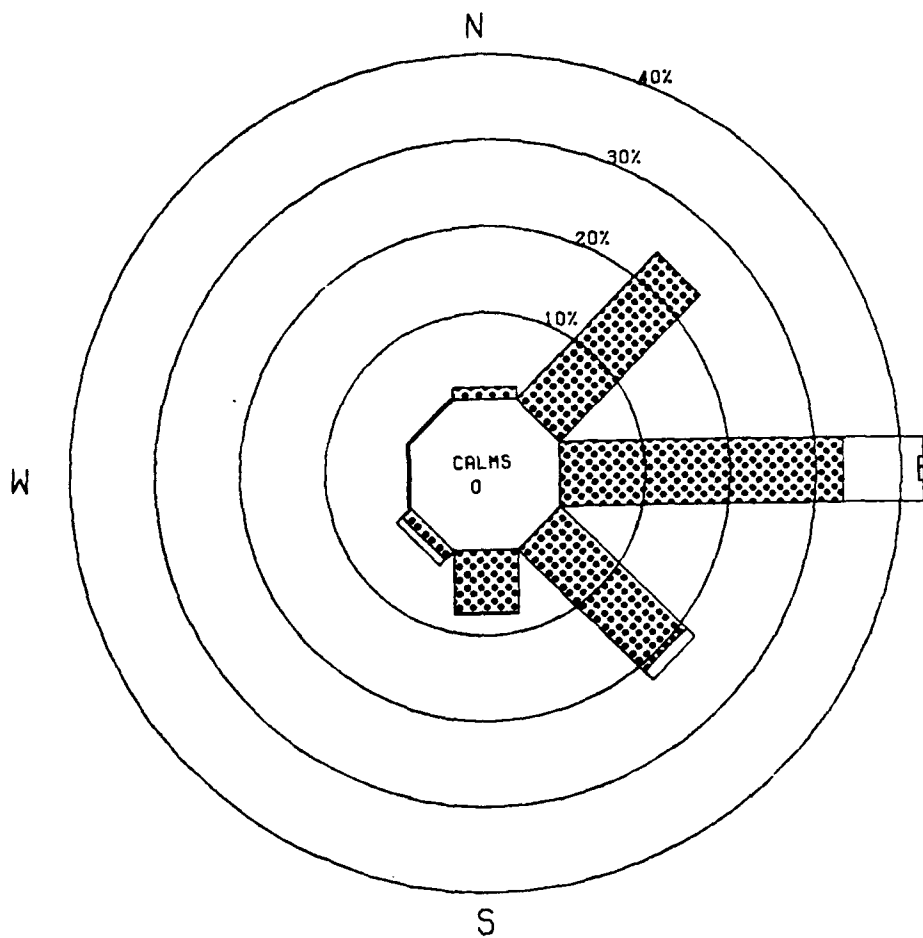


Figure 30. Wind Direction Histogram for September 1989



NUMBER OF OBSERVATIONS -- 424
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

PERCENTAGE OF OBSERVATIONS	WHICH AT SPEEDS ARE OF
	01-10 KNOTS
	11-16 KNOTS
	17-27 KNOTS
	>27 KNOTS

Figure 31. Wind Rose for September 1989

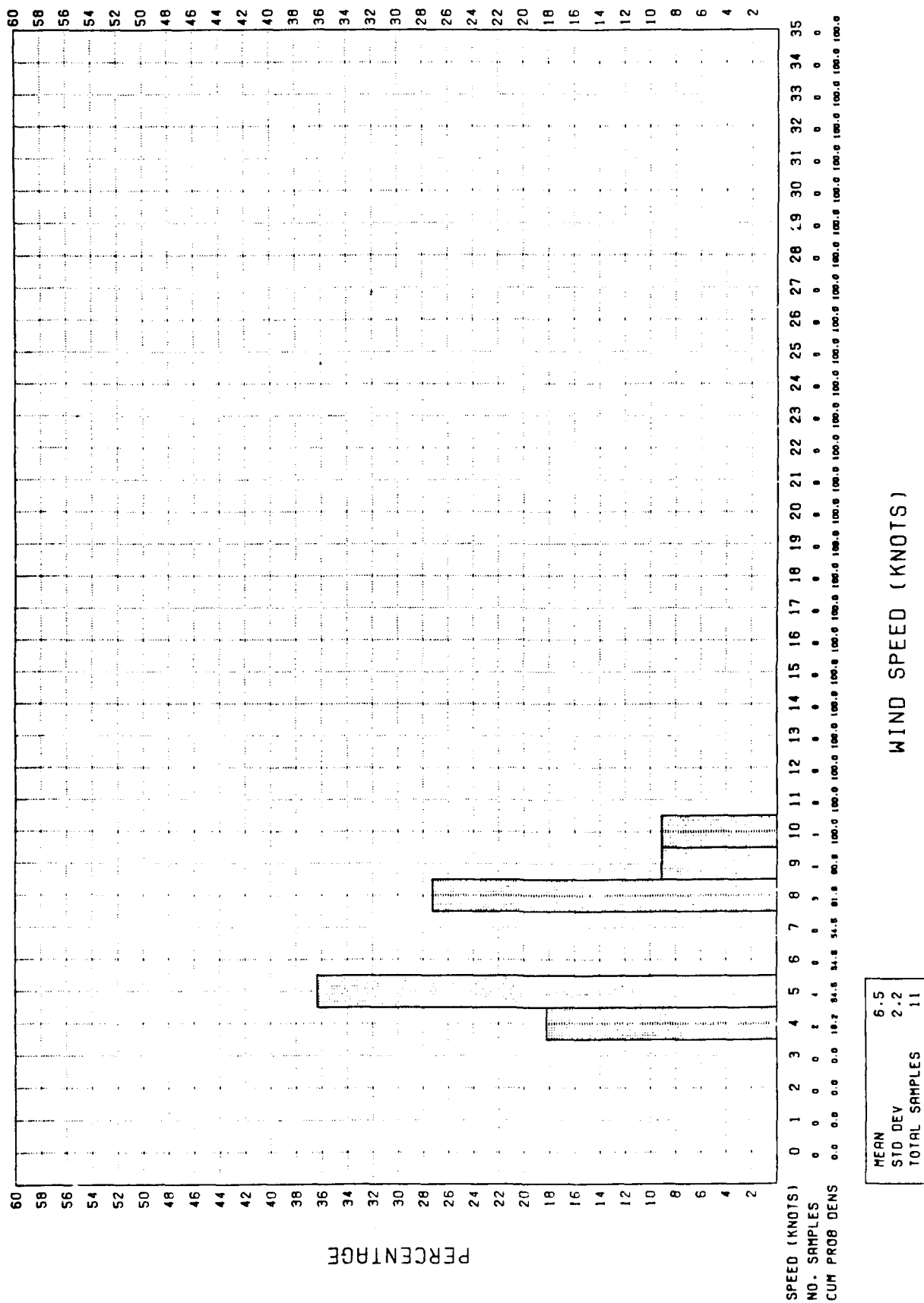


Figure 32. Wind Speed Histogram for October 1989

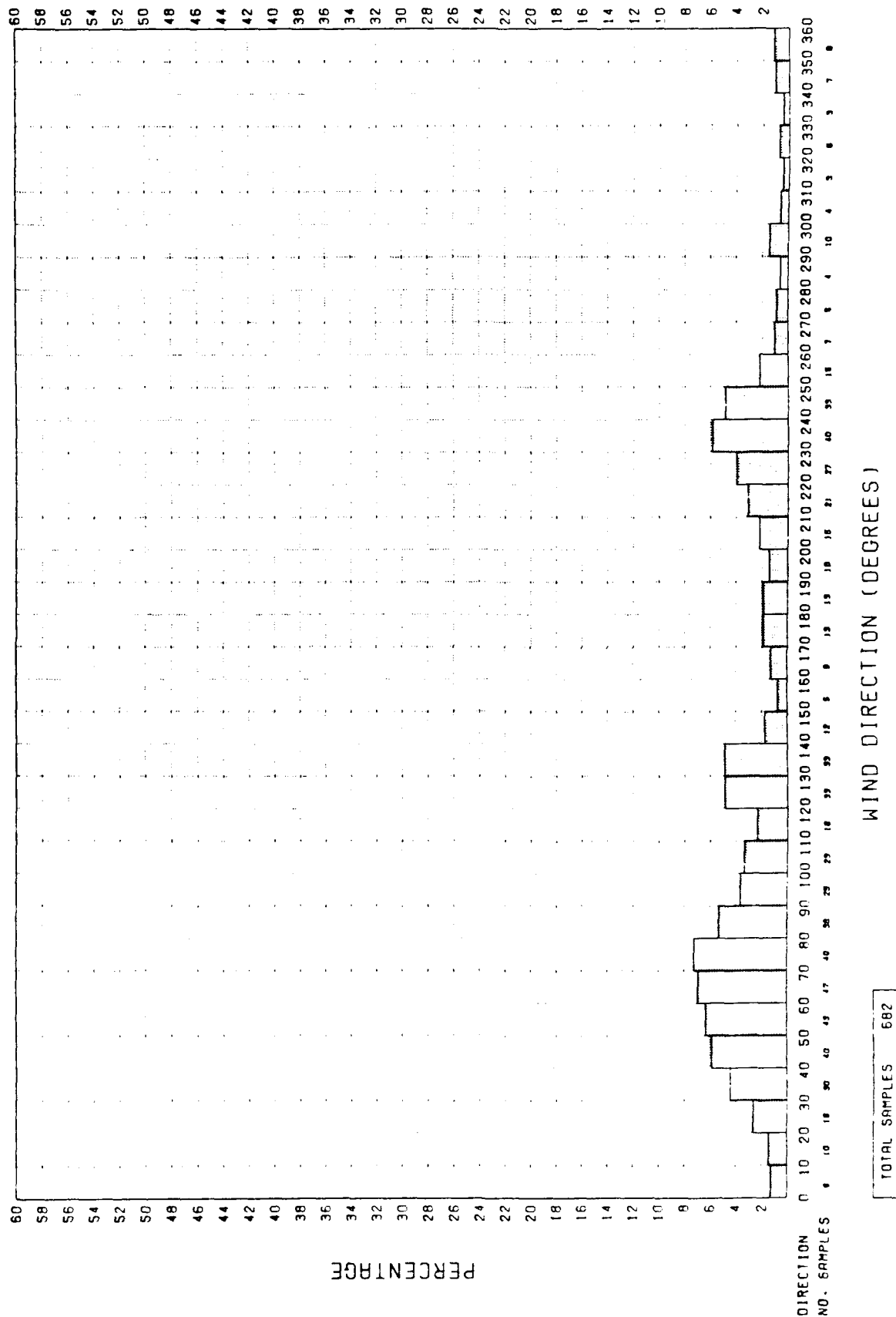
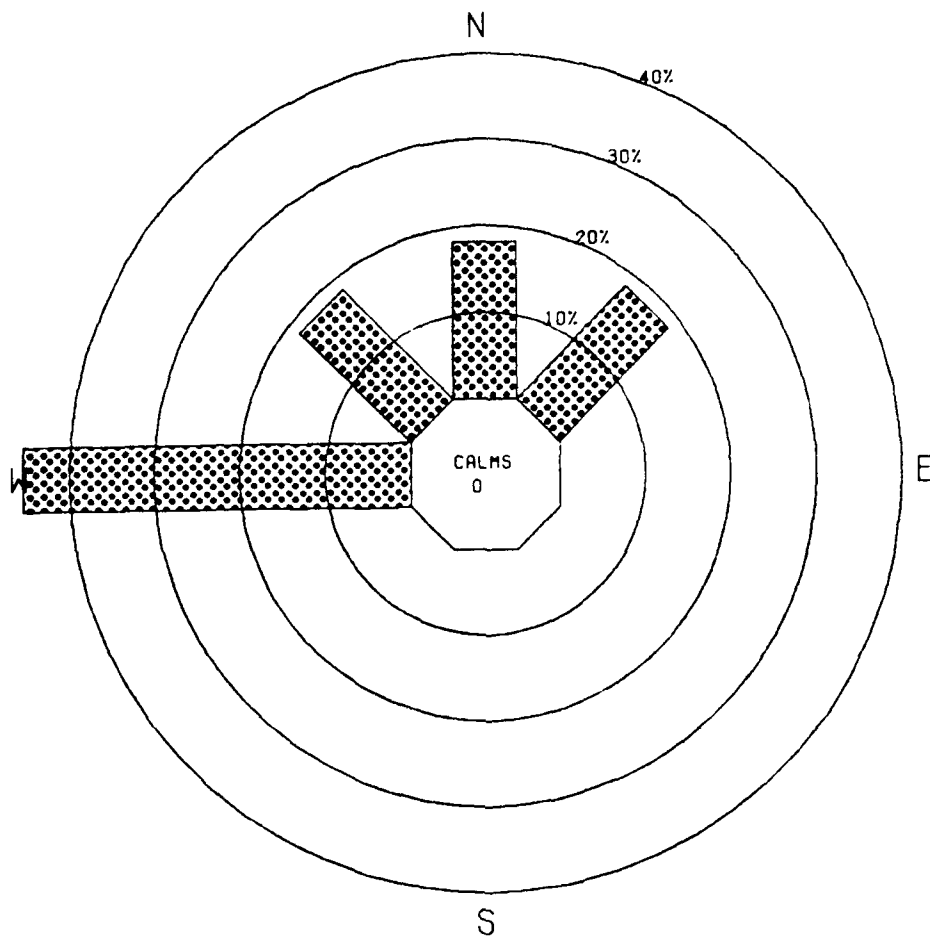


Figure 33. Wind Direction Histogram for October 1989



NUMBER OF OBSERVATIONS -- 11
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

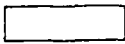
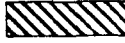
PERCENTAGE OF OBSERVATIONS	WHICH AT SPEEDS ARE OF
	01-10 KNOTS
	11-16 KNOTS
	17-27 KNOTS
	>27 KNOTS

Figure 34. Wind Rose for October 1989

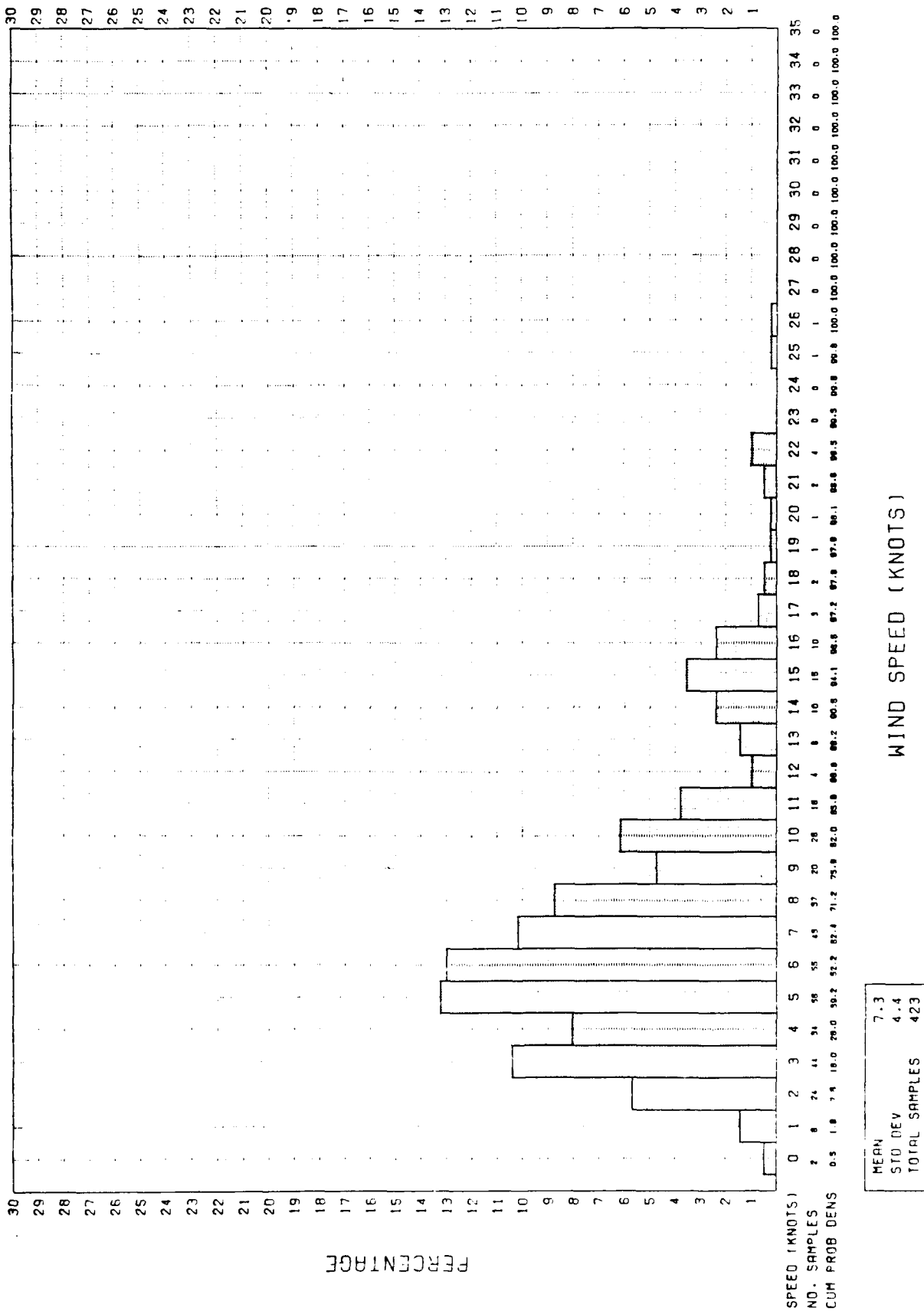


Figure 35. Wind Speed Histogram for December 1989

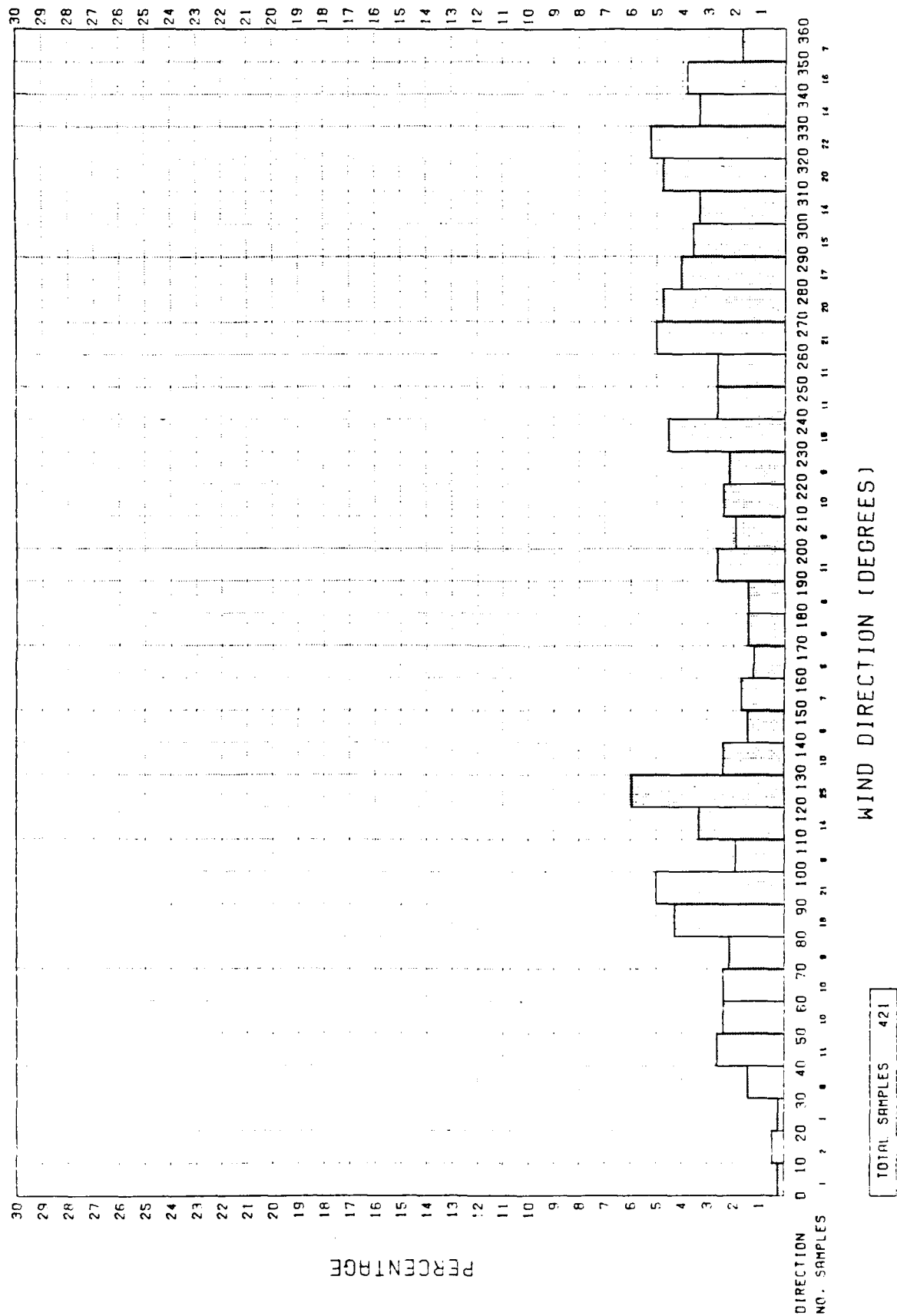
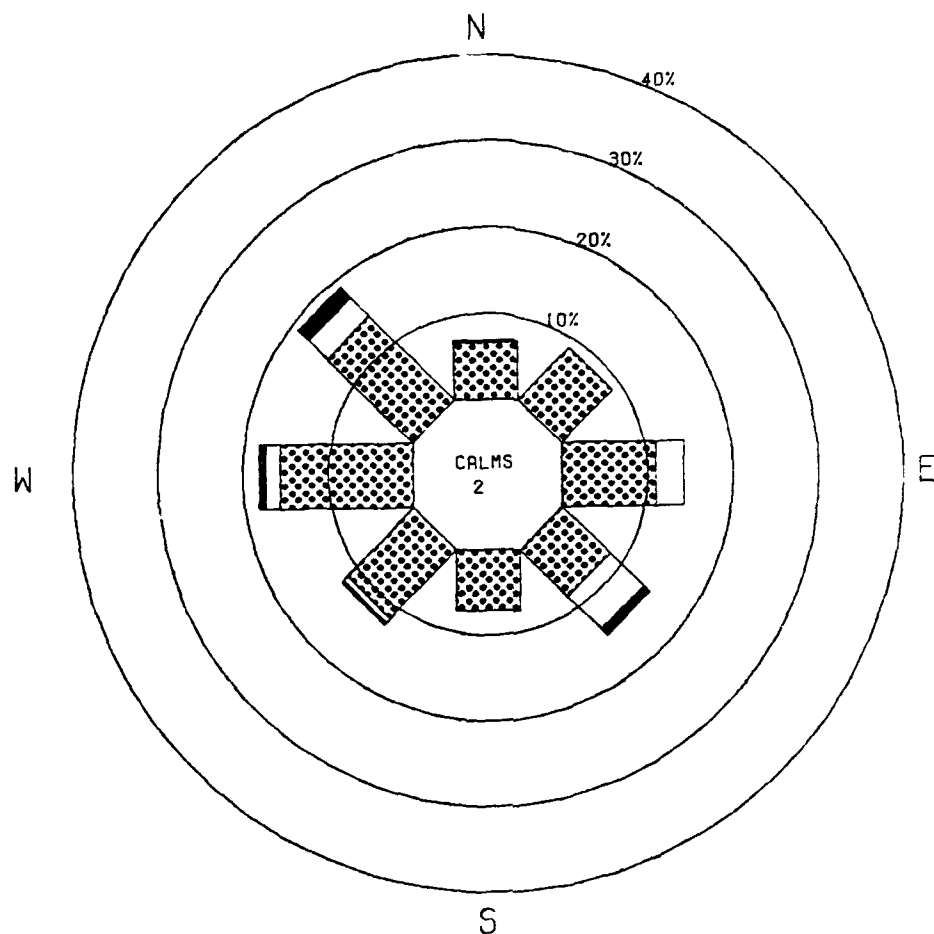


Figure 36. Wind Direction Histogram for December 1989



NUMBER OF OBSERVATIONS -- 423
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

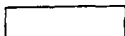
PERCENTAGE OF OBSERVATIONS	WHICH AT SPEEDS ARE OF
	01-10 KNOTS
	11-16 KNOTS
	17-27 KNOTS
	>27 KNOTS

Figure 37. Wind Rose for December 1989

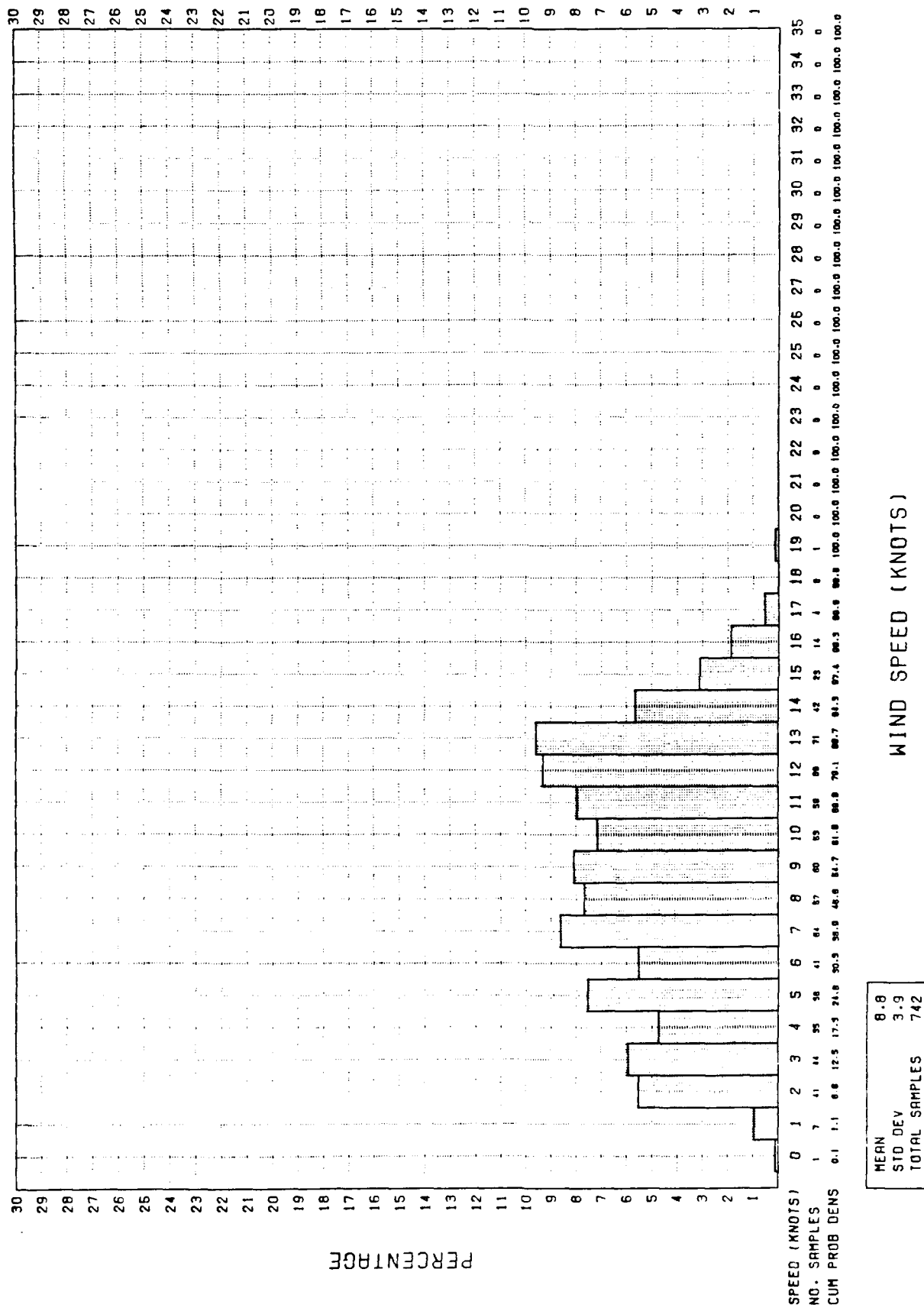


Figure 38. Wind Speed Histogram for January 1990

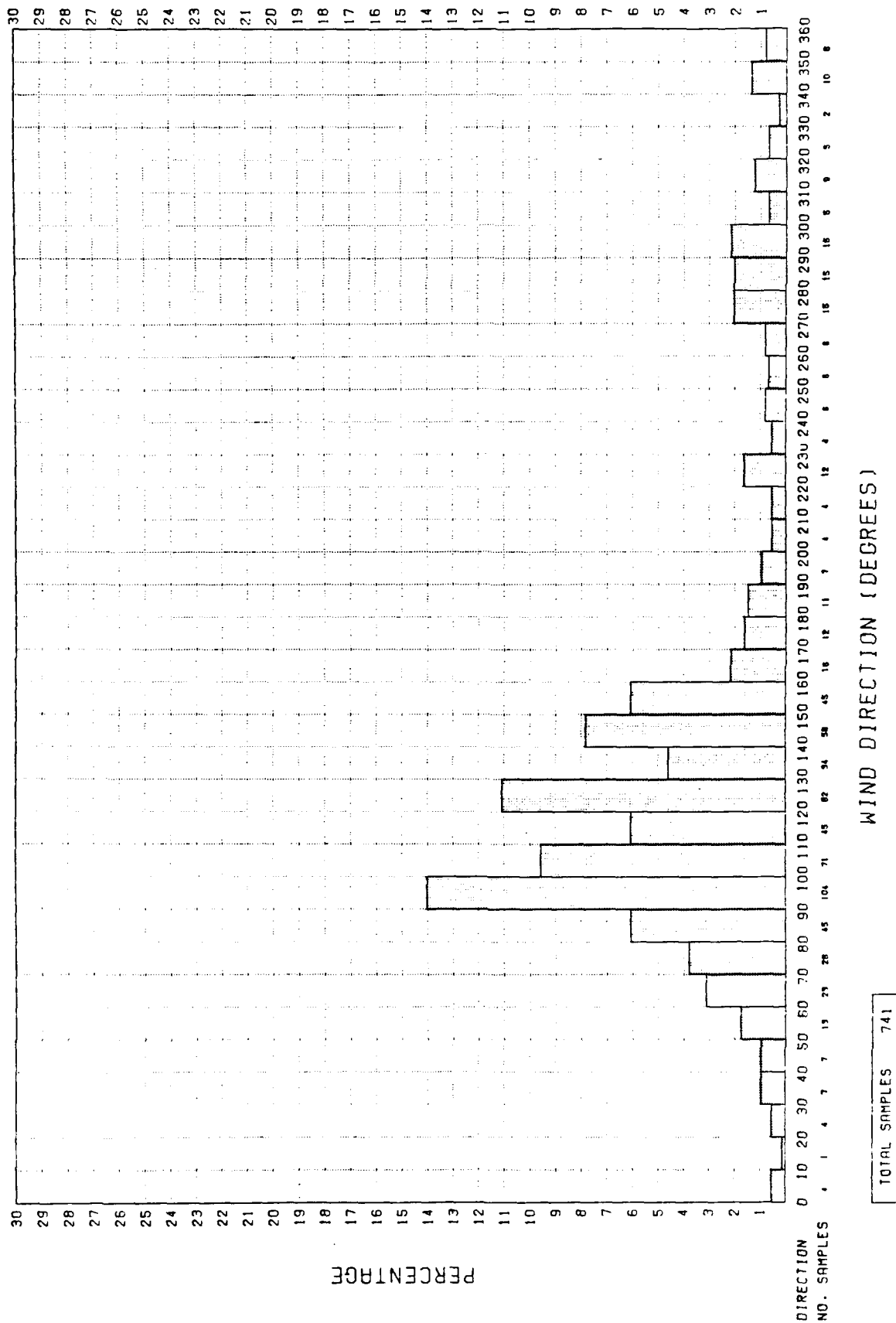
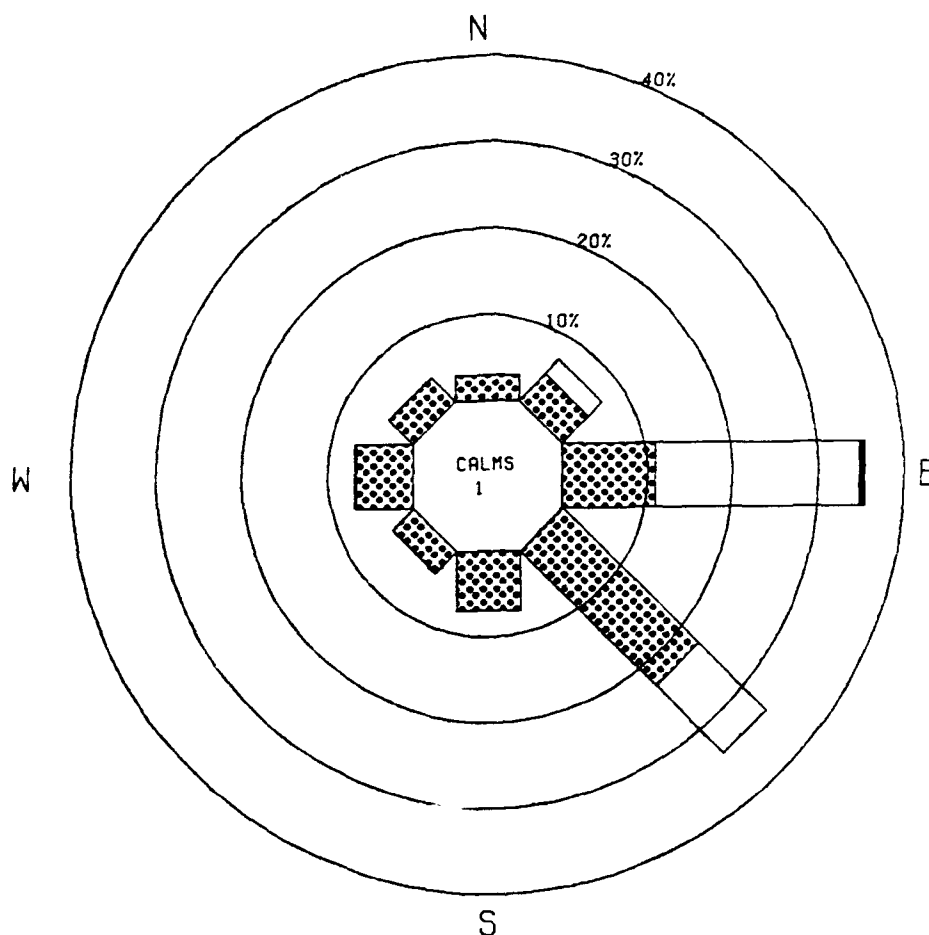


Figure 39. Wind Direction Histogram for January 1990



NUMBER OF OBSERVATIONS -- 742
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

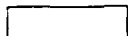
PERCENTAGE OF OBSERVATIONS	WHICH ARE	AT SPEEDS OF
		01-10 KNOTS
		11-16 KNOTS
		17-27 KNOTS
		>27 KNOTS

Figure 40. Wind Rose for January 1990

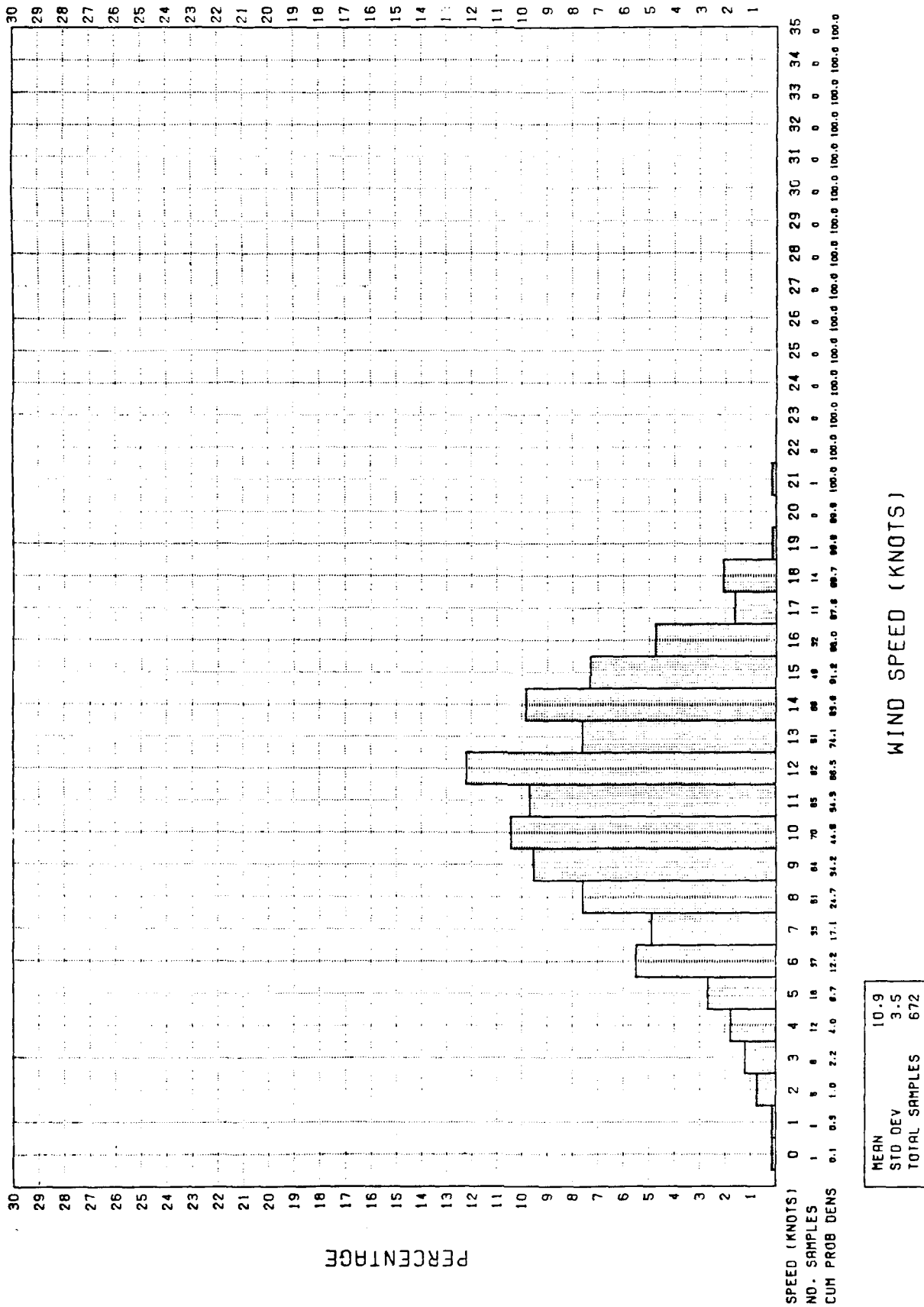


Figure 41. Wind Speed Histogram for February 1990

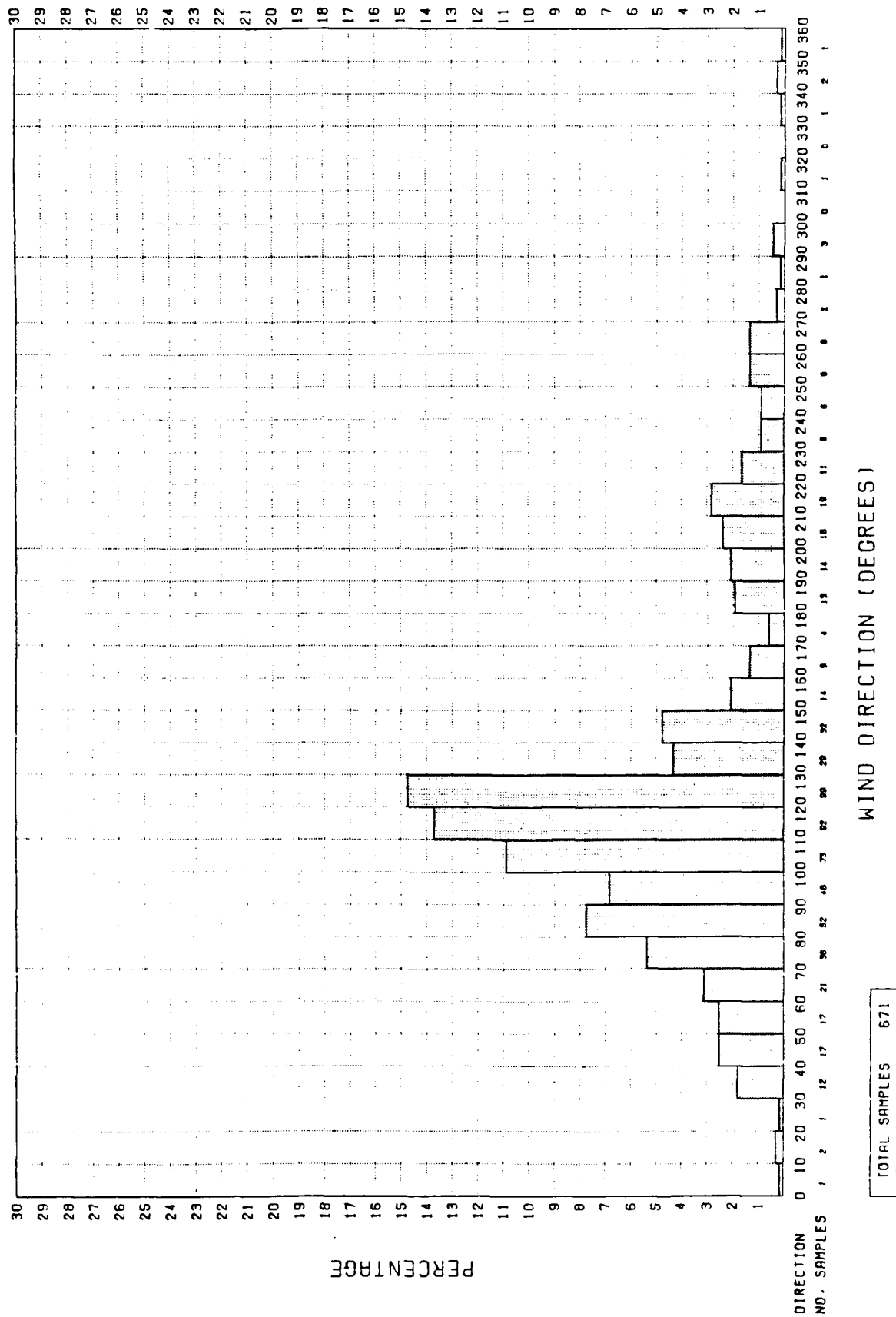
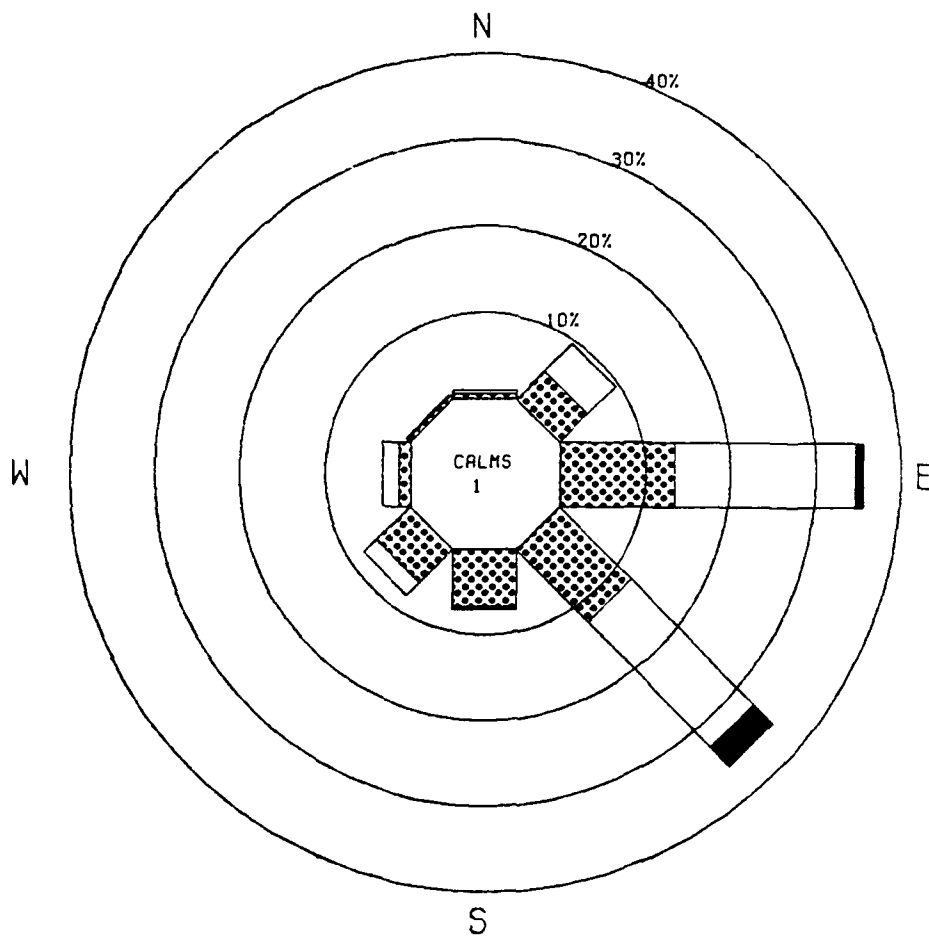


Figure 42. Wind Direction Histogram for February 1990



NUMBER OF OBSERVATIONS -- 672
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

PERCENTAGE OF OBSERVATIONS	WHICH ARE	AT SPEEDS OF
		01-10 KNOTS
		11-16 KNOTS
		17-27 KNOTS
		>27 KNOTS

Figure 43. Wind Rose for February 1990

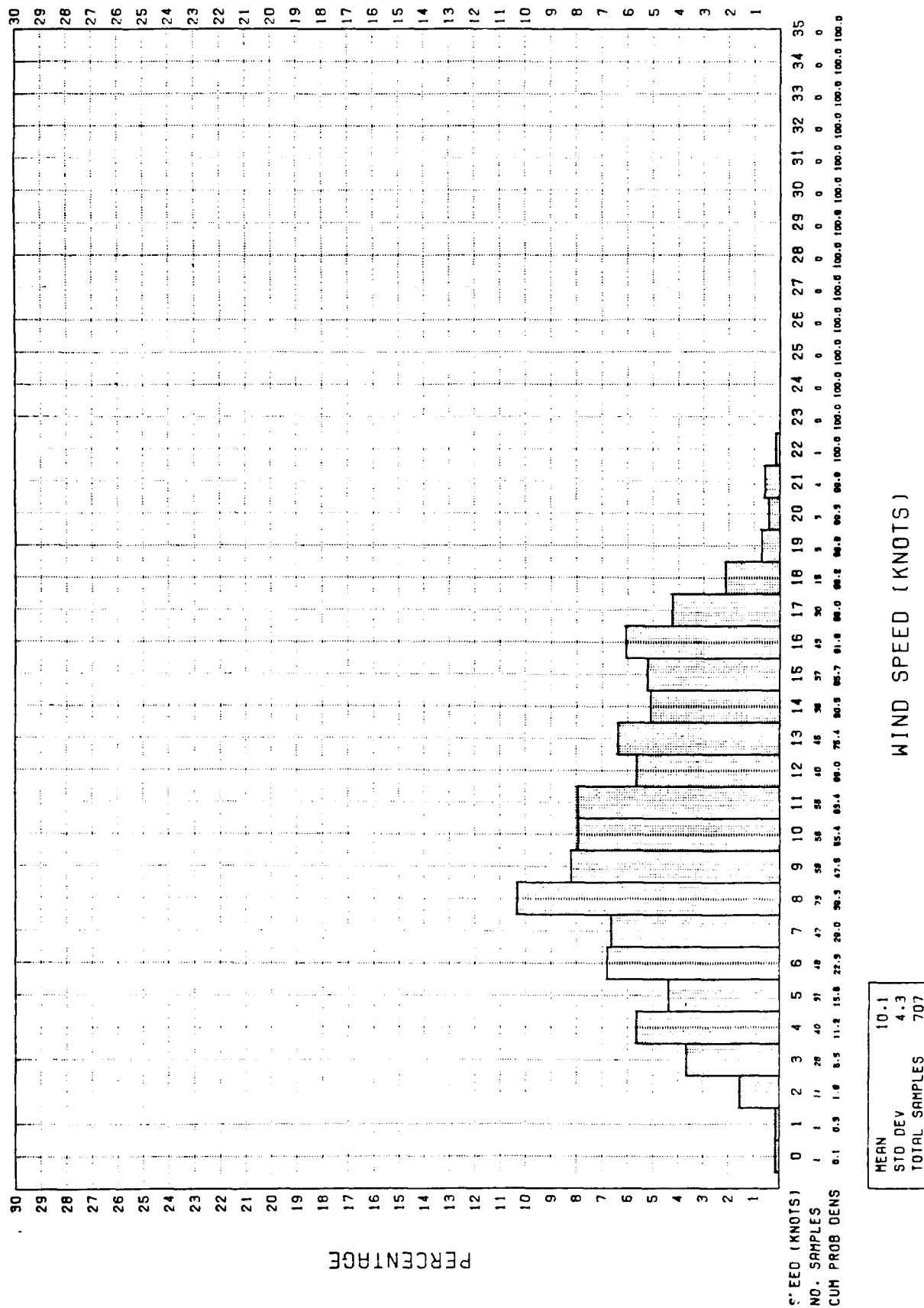


Figure 44. Wind Speed Histogram for March 1990

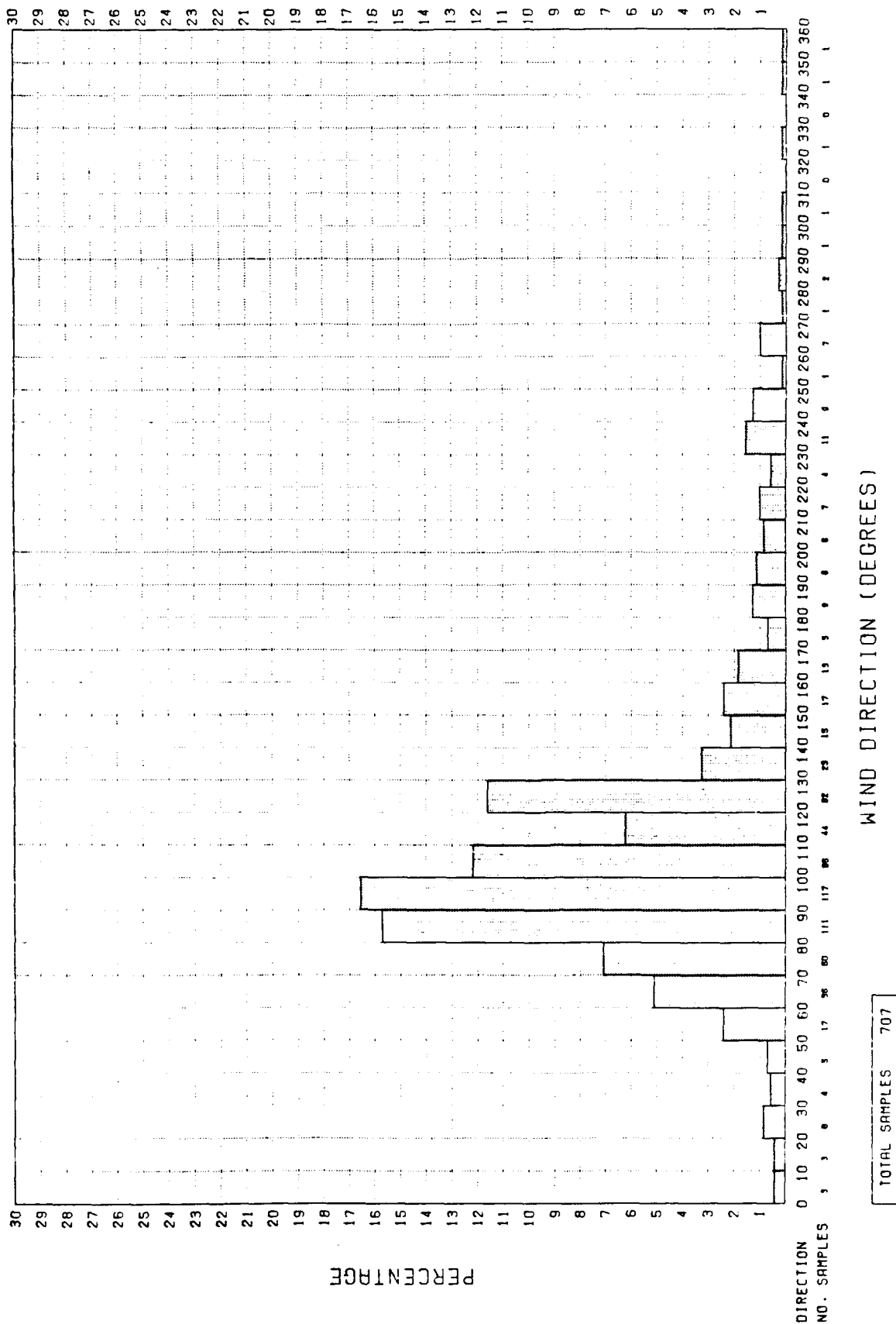
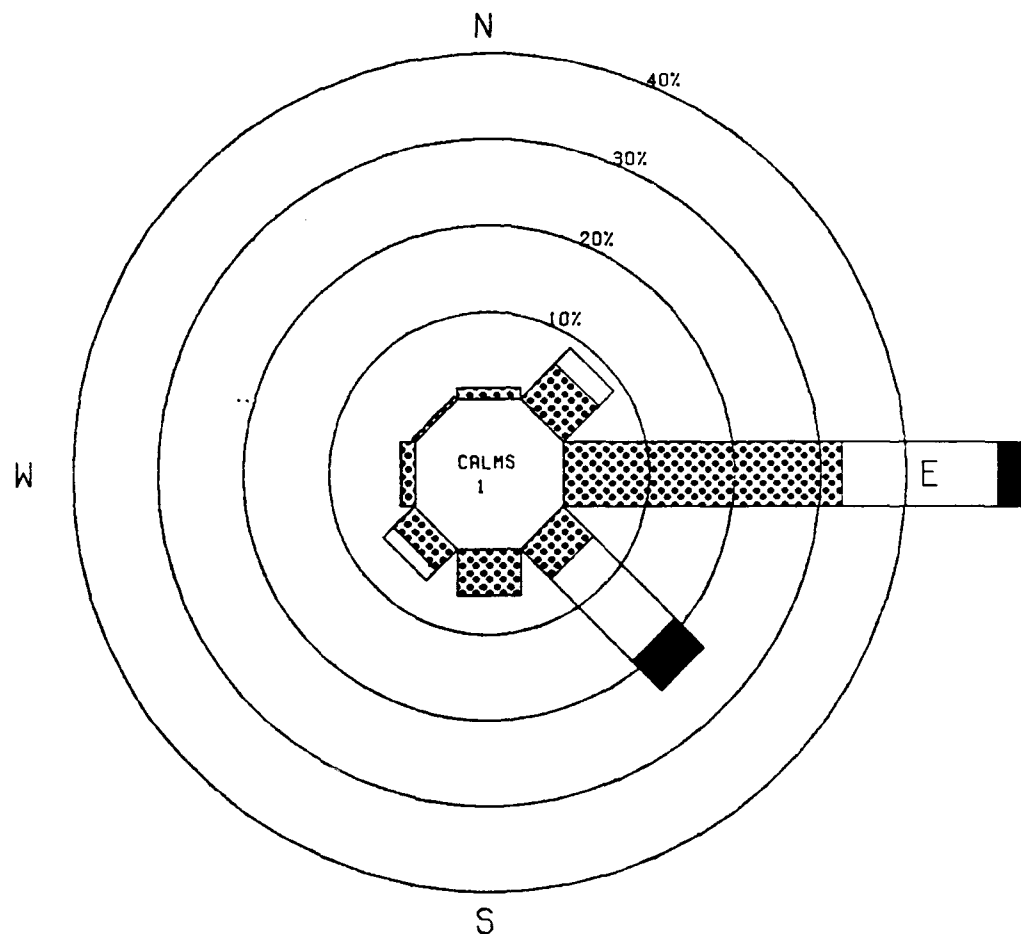


Figure 45. Wind Direction Histogram for March 1990



NUMBER OF OBSERVATIONS -- 707
 THE CIRCLES INDICATE THE PERCENTAGE
 OF OBSERVATIONS FOR EACH DIRECTION

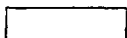
PERCENTAGE OF OBSERVATIONS	WHICH ARE	AT SPEEDS OF
		01-10 KNOTS
		11-16 KNOTS
		17-27 KNOTS
		>27 KNOTS

Figure 46. Wind Rose for March 1990

Table 1. Monthly Data

Month	Mean (knots)	Std. Dev. (knots)	Samples
Apr 89	7.3	3.3	87
May 89	7.3	3.5	744
Jun 89	8.9	3.0	714
Jul 89	8.6	3.1	742
Aug 89	7.4	3.7	743
Sep 89	7.1	2.6	424
Oct 89	6.5	2.2	11
Nov 89	-	-	0
Dec 89	7.3	4.4	423
Jan 90	8.8	3.9	742
Feb 90	10.9	3.5	672
Mar 90	10.1	4.3	707

DATA BASE HOURLY AND 4-HOUR AVERAGES

In an attempt to characterize the mean daily behavior of the observed wind speeds, the observations for each hour of the day were averaged over the entire data base. The resulting hourly average is shown in figure 47. The corresponding deviations are shown in figure 48.

Figure 47 indicates the presence of a diurnal cycle. The 2000 to 0800 lull is a 12-hour occurrence, and the 1000 to 1600 high is 6 hours in duration. The corresponding spectral contributions were identified in figure 10.

As a final averaging presentation, each day was divided into six 4-hour intervals, and the observations over the entire data base for each interval were averaged. The resulting average and deviation plots are shown in figures 49 and 50.

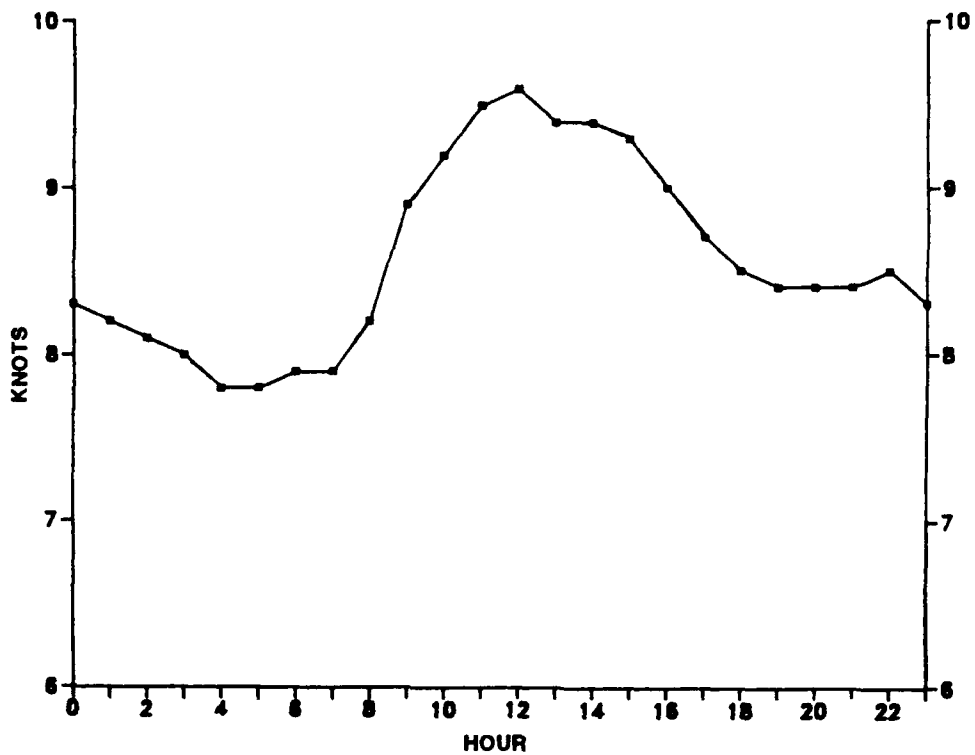


Figure 47. Data Base Hourly Averages

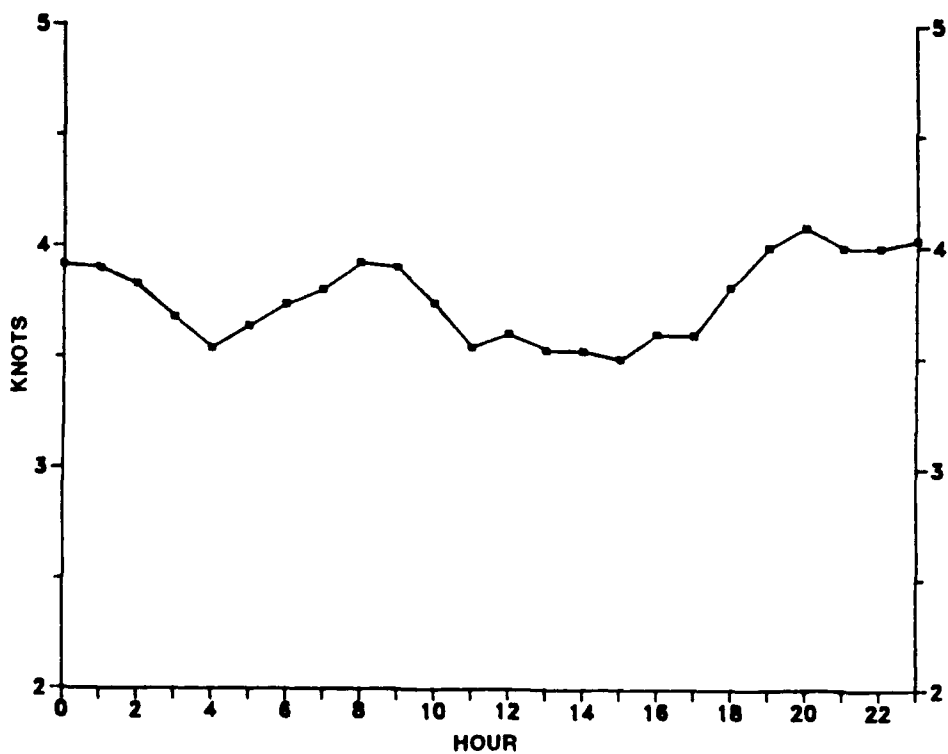


Figure 48. Data Base Hourly Deviations

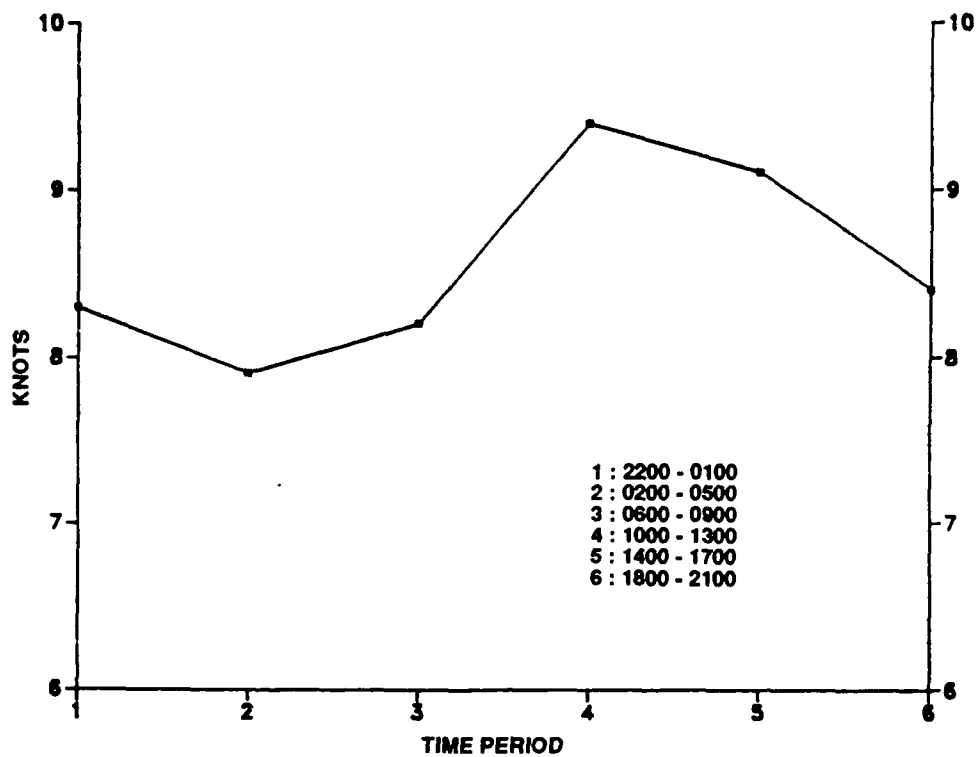


Figure 49. Data Base 4-Hour Averages

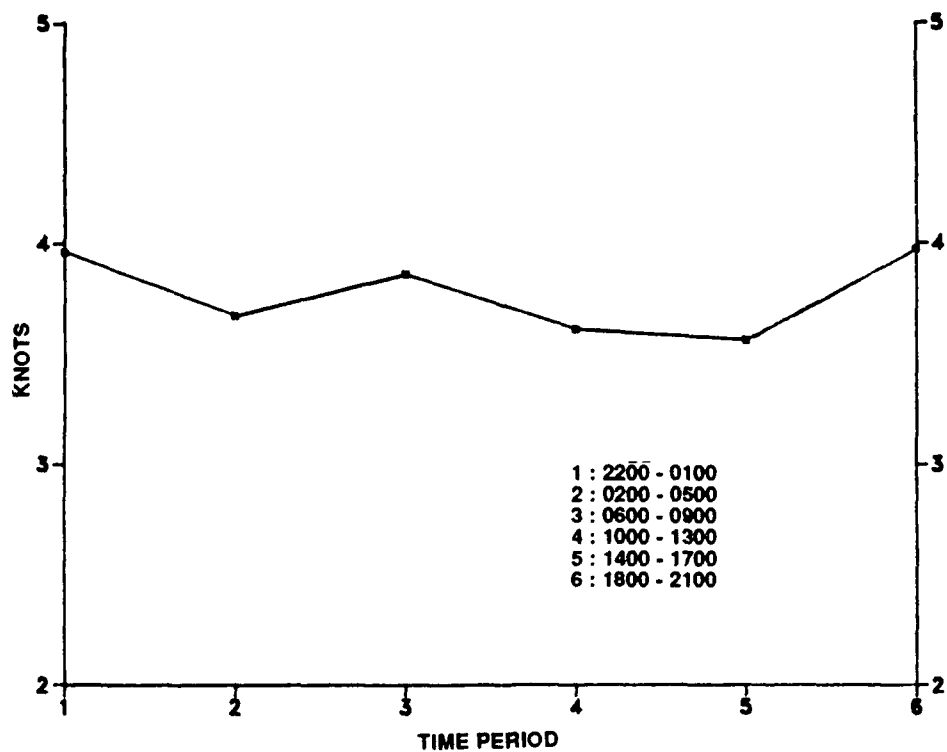


Figure 50. Data Base 4-Hour Deviations

CONCLUSIONS

Statistical analysis of the Eleuthera wind data base measured intermittently from 27 April 1989 to 30 March 1990 revealed several broad conclusions. Figure 2 summarized the data base in an empirical distribution function and showed a median wind speed of 8.5 knots. It also showed that 93 percent of the observations (10-minute averages) fell below 15 knots and 19 percent below 5 knots.

Figure 3 indicated that the wind speed density function was similar to a chi-square with 9 degrees of freedom and revealed a mode of 7 knots. The chi-square probability model predicted a mean of 9 knots and a deviation of 4.3 knots. The monthly wind speed was shown to have a larger variability during October through March compared with the wind speed during April through September (shown in figures 4 and 5). The predominant wind direction was the east-southeast and hourly sustained winds of 20 knots or higher were rare, as indicated in figure 9.

Examination of the estimated power spectrum in figure 10 showed a broad spectral contribution for the 8- to 12-hour periodic components. On a diurnal basis, figure 47 indicated a pattern of strongest winds in the 1000 to 1600 interval, and of weakest winds in the 1900 to 0900 interval.

A 3-year data base of wind observations at AUTECH has been compiled covering the period from January 1987 through August 1990. Published results for calendar years 1988 (reference 1) and 1989 (reference 2) reveal a mean wind speed of 12 and 11 knots, respectively. The mean wind speed for this study was 9 knots. It is interesting to note that for the 1988 and 1989 data bases, the average cumulative distribution for 20-knot winds was 96 and 98 percent, respectively, and 99 percent for Eleuthera. The corresponding 15-knot cumulative distribution values were 70 and 80 percent for AUTECH in 1988 and 1989, respectively, and 93 percent for Eleuthera. This indicates that 93 percent of the observed 10-minute average wind speeds were 15 knots or less for Eleuthera, while the observed average winds of 15 knots or less at AUTECH were significantly less frequent.

A detailed comparison of AUTECH and Eleuthera data acquired over the same time interval will be presented in a future report.

REFERENCES

1. H. C. Velez, "Wind and Barometric Pressure in the TOTO, Bahamas: A Summary of 1988 Observations," NUSC Technical Document 6856, Naval Underwater Systems Center, Newport, RI, 1 December 1989 (UNCLASSIFIED).
2. H. C. Velez, "Wind and Barometric Pressure in the TOTO, Bahamas: A Summary of 1989 Observations," NUSC Technical Document 6978, Naval Underwater Systems Center, Newport, RI, 4 January 1991 (UNCLASSIFIED).

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