TURBULENCE CHARACTERISTICS AT HOWDEN WIND PARK I

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Abstract

Turbulence measurements began at Howden Wind Park I in August 1986. A program was undertaken to measure gustiness in the wind and try to relate this to wind parameters commonly measured. Also, horizontal wind shear data was collected using pairs of towers separated by one rotor diameter. All measurements were made at turbine hub height.

Results show that both spacial and temporal fluctuations in the wind flow tend to increase in magnitude as mean and standard deviation of speed increase. The level of the turbulent fluctuations is apparently increased by turbine wake effects and also can be influenced by terrain features. Due to diverging patterns in the gust parameters and turbulence intensity, as functions of mean speed, the use of turbulence intensity as an indicator of turbulence levels is cautioned.

Introduction

Howden Wind Park I is located on Section 30 in the northern Altamont Pass of California, approximately 50 miles east of San Francisco. The Wind Park consists of 75 Howden 330/33 (330 kW, 33 meter rotor) wind turbines.

Turbulence measurements at the Wind Park began in August 1986 with three met towers measuring hourly means and standard deviations of wind speed, direction and vertical velocity. Wind speed and direction were measured using R.M. Young propeller vane anemometers. R.M. Young propeller anemometers were used for measurements of vertical component. Datalogging was performed using Campbell Scientific 21X microloggers.

In September 1987 turbulence measurements began at six more sites using Campbell CR10 microloggers, Maximum cups and NRG vanes. In the spring of 1988 an array of seven temporary met towers was installed to measure turbulence levels in the wake of operating turbines. All of these had high response R.M. Young propeller vanes and vertical velocity sensors located at hub height (25 meters (82 feet)). Campbell 21X dataloggers were used for data acquisition.

Beyond collecting means and standard deviations, the types of data that have been collected include wind speed distributions, speed maxima and minima, gust magnitudes, and distributions and extremes of horizontal wind shear. In this paper, relationships between some of these quantities and the more common measurements (mean and standard deviation of speed) are explored.

Basic Turbulence Measurements

During the period that the Howden Wind Park was without blades on the turbines, baseline turbulence measurements were made on an hourly basis. Turbulence levels since the Wind Park came back on line can be compared to those when the Wind Park was inoperative.

Turbulence intensity (TI), defined as the standard deviation of wind speed divided by the mean wind speed, is a term commonly used to describe turbulence levels. Figure 1 shows the variation in mean turbulence intensity as a function of wind speed for the period May through July in 1987 and 1988 at two met sites, H7 and H8. Both measurements were made at hub height. The figure shows decreasing TI with increasing wind speed, which is the typical pattern. The mean TI in 1988 has increased over the 1987 levels at both sites, moreso at site H7 than H8. Site H8 has one row of turbines operating in the prevailing upstream direction and site H7 has two rows upstream. It cannot be proven that the increases observed here are due entirely to wind turbine array effects. However, our tests have shown that operating turbines can cause turbulence increases of the order shown here.

Beyond calculating turbulence intensities, the means and standard deviations can be used to estimate other characteristics of the wind.

Assuming a normal, or Gaussian, distribution of wind speed samples, the maximum value sampled would be approximately three standard deviations above the mean. Figure 2 shows a comparison of estimated hourly maximum wind speed (using the above method, mean + three standard deviations) versus observed maximum speed. Good agreement is found between the two. A similar estimation of hourly minimum wind speeds (three standard deviations below the mean) shows like agreement to the observed values.

The assumption of a normal distribution was apparently valid for the estimation of hourly maximum wind speeds. This assumption can be tested further by comparing observed wind speed distributions to a calculated Gaussian distribution. Comparison of four-minute wind speed distributions, sampled at 1 Hz, and Gaussian distributions based on the mean speed and four minute standard deviation show that, to a fair

Figure 1.
MEAN TURBULENCE INTENSITY VS WIND SPEED

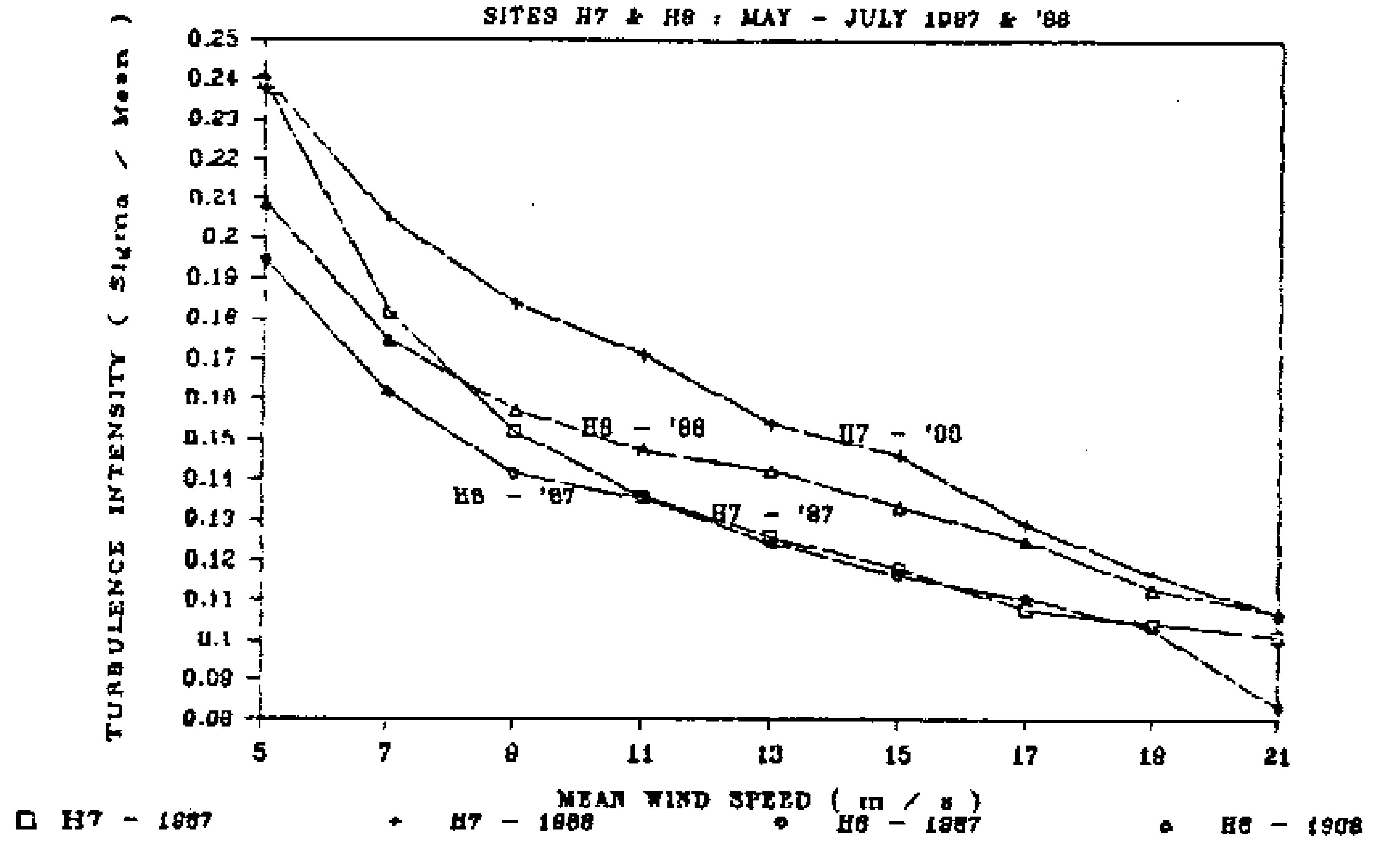


Figure 2.
ESTIMATED VS OBSERVED MAX WIND SPEED

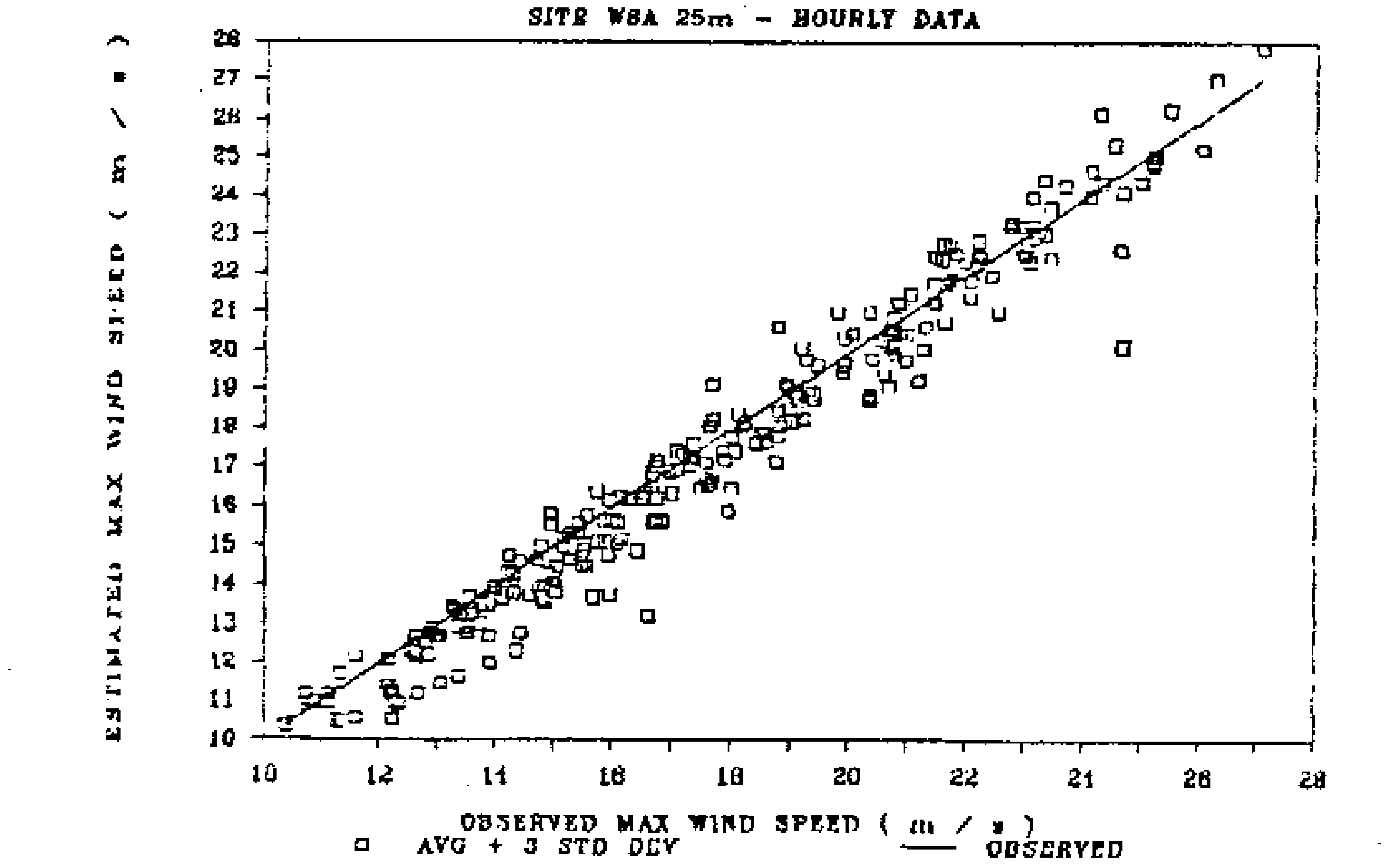


Figure 3.
SITE W6A GUST COUNT

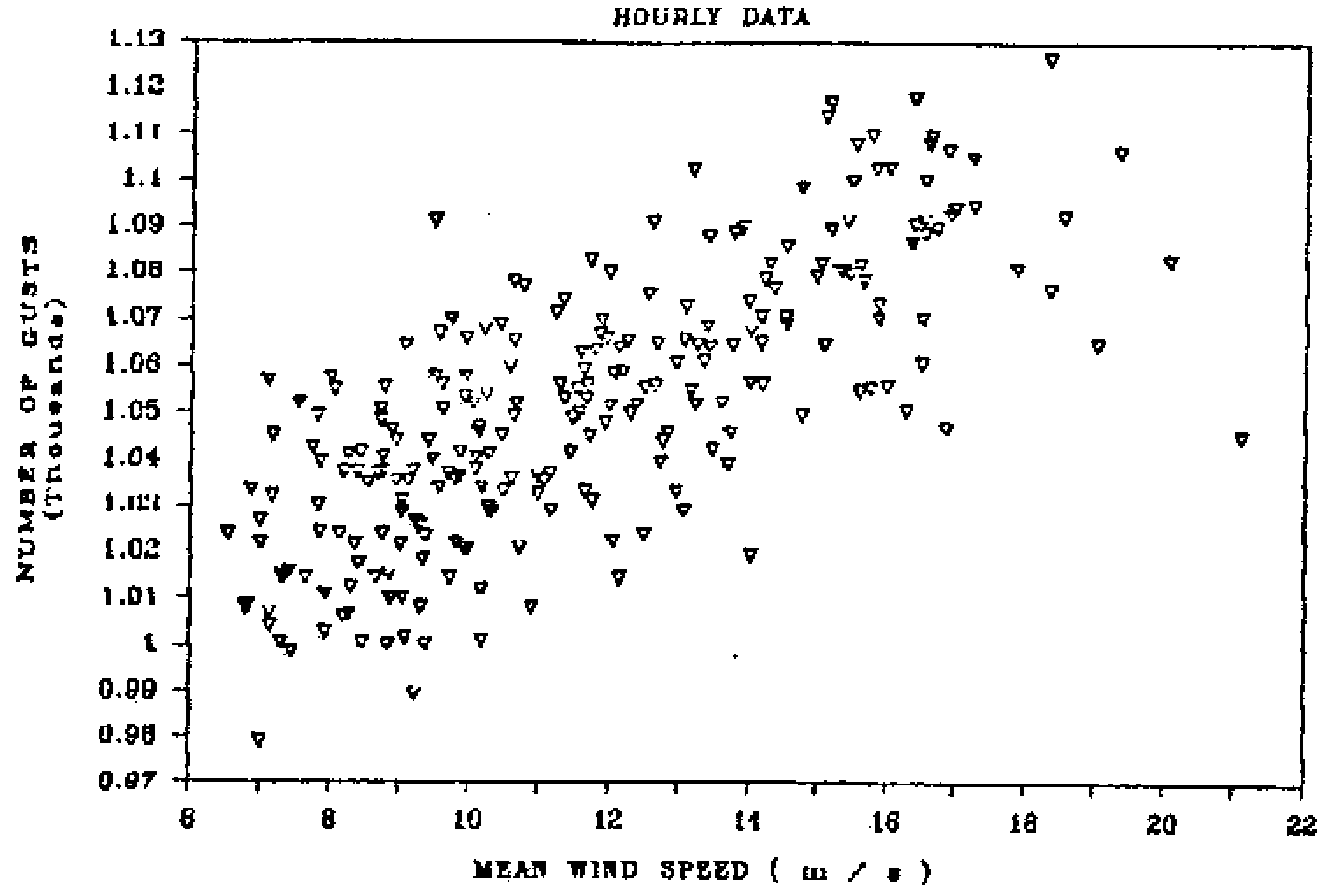
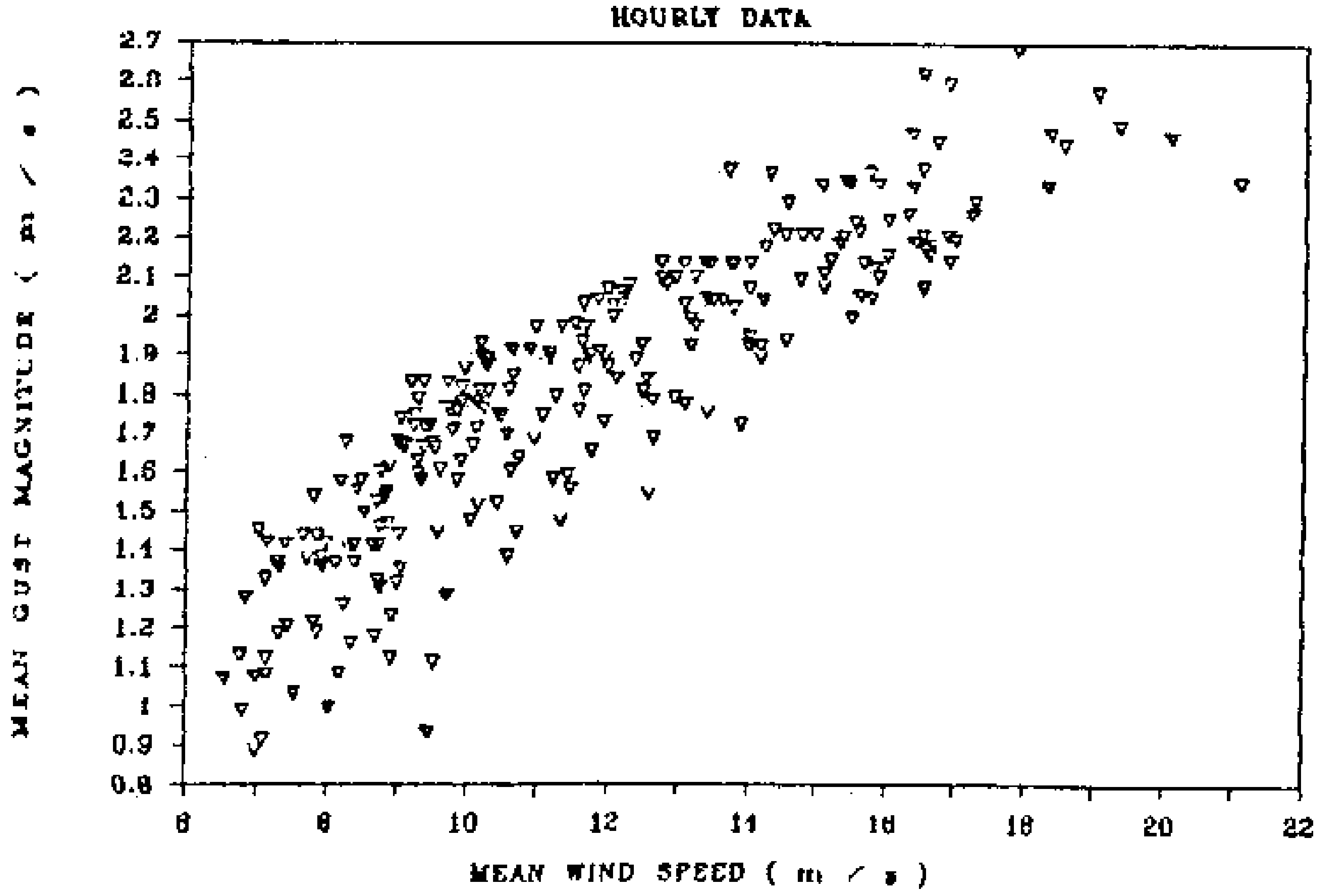


Figure 4.
SITE W6A MEAN GUST MAGNITUDE



approximation, the distribution of one-second samples is Gaussian. However, there are frequent errors between the observed and Gaussian distributions, the largest differences tending to occur in the speed ranges near the mean.

Knowing the exact or approximate wind speed distribution does not give any insight into how the wind behaved during the time period in question. That is, how the wind speed fluctuated from one second to another; i.e., the nature of the gusts experienced.

Gust Measurements

To examine the gustiness, a program for the Campbell 21X datalogger was installed which would, on an hourly basis sampling at 1 Hz, record the number of gusts, the mean gust magnitude, mean gust duration, maximum positive and negative gust magnitudes (and their durations) and the maximum positive and negative one-second gust magnitudes. This was restricted to conditions such that the wind speed stayed above 2.7 m/s (6 mph) for the entire hour. The program was installed at two met towers which were part of the turbine array effects monitoring network. These are known as site W6A and site WG.

Site W6A is located near the center of the Wind Park on the highest hill on the property, approximately 6.5 rotor diameters (RD) downstream of the nearest line of turbines, the I line. Site WG is located just upstream of the easternmost line of turbines on the Wind Park, the G line. It is approximately 10 to 12 RD (depending on wind direction) downstream of the nearest line of turbines, the F line. Sites W6A and WG are roughly in line with one another in the prevailing summer southwesterly flow.

The gust characteristics measured at site W6A will be discussed and then those at site WG will be compared to W6A.

The first parameters analyzed are the hourly gust count (the number of gusts recorded) and mean gust magnitude. The gust count is defined here as the number of times a lull or relative wind speed minimum was recorded. Thus, a complete gust would begin from a lull, continue through the peak and end at the next lull. This differs from some definitions of a gust which use the mean speed during a given time period as the reference for gusts. Gust magnitude is defined as the difference in wind speeds, referenced to a lull speed, for positive gust magnitude and referenced to a gust peak speed for negative magnitudes. One second gusts are merely the difference between two successive speed measurements. The mean gust magnitude is the mean absolute speed difference from lull to peak, or peak to lull, of the mean gust.

Figures 3 and 4 show the hourly gust count versus mean wind speed and the mean gust magnitude versus mean wind speed, respectively. Both show similar tendencies - to increase with increasing wind speed. These same two parameters plotted versus standard deviation of wind speed show a similar pattern.

A similar pattern is observed when maximum gust magnitudes are compared to mean speed. Figure 5 shows a plot of hourly maximum positive and negative complete and one-second gust magnitudes versus mean speed at site W6A. The patterns for positive and negative gusts are quite symmetrical, indicating that the hourly maximum positive and negative gusts are nearly equal in absolute magnitude. If one plots these same gust parameters as a function of standard deviation of wind speed, a similar pattern is observed. In both cases the maximum gusts, complete or one-second, tend to increase in magnitude as wind speed or standard deviation of wind speed increase.

So, not only do the mean gusts increase in number and magnitude with increasing mean speed, but the extreme gusts also increase in magnitude. Although turbulence intensity decreases with increasing mean speed (Figure 1), it would be incorrect to assume that this indicates a smoother or more benign wind environment in which to operate turbines. Due to this inconsistency, it is more meaningful to use standard deviation of wind speed, rather than TI, to describe turbulence levels.

The turbulent variations in wind speed can also be viewed as variations in the power in the wind. This calculation was performed for the one-second maximum gusts and the resulting power ratios are plotted against the lull (lower) speed of the one-second gust in Figure 6. For one-second gusts with a lull speed of 12 m/s, rated speed for the HWP 330/33 wind turbine, one-second power increases of 400% are observed, which represents a rather dramatic increase in available power.

Figure 7 shows a bin-sorted daily frequency distribution of one-second gusts from site W6A for several days having different daily mean speeds. Days having higher mean speeds also have greater frequencies of occurrence of one second gusts with higher magnitudes. This is consistent with the hourly data, which showed higher magnitude mean and maximum gusts with higher mean speeds.

Comparison of Site WG to W6A

The point of comparing the gust parameters at the two sites is to determine if there is a consistency in the relationships between parameters such as mean and standard deviation of speed and gust parameters. Are the

Figure 5.

MAX 1 SEC & COMPLETE GUST MAGNITUDES

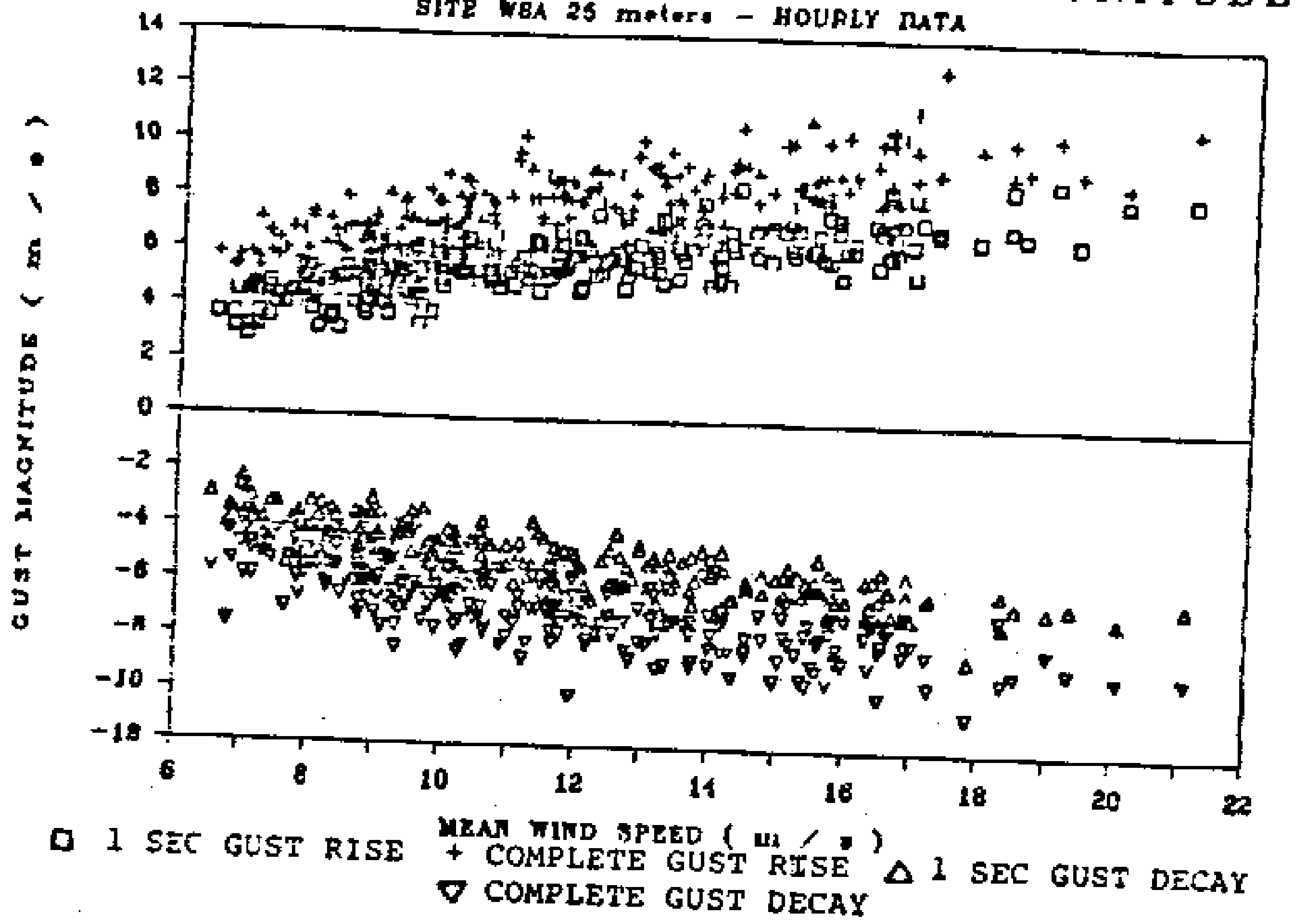


Figure 7.

OBSERVED FREQUENCY OF 1 SECOND GUSTS

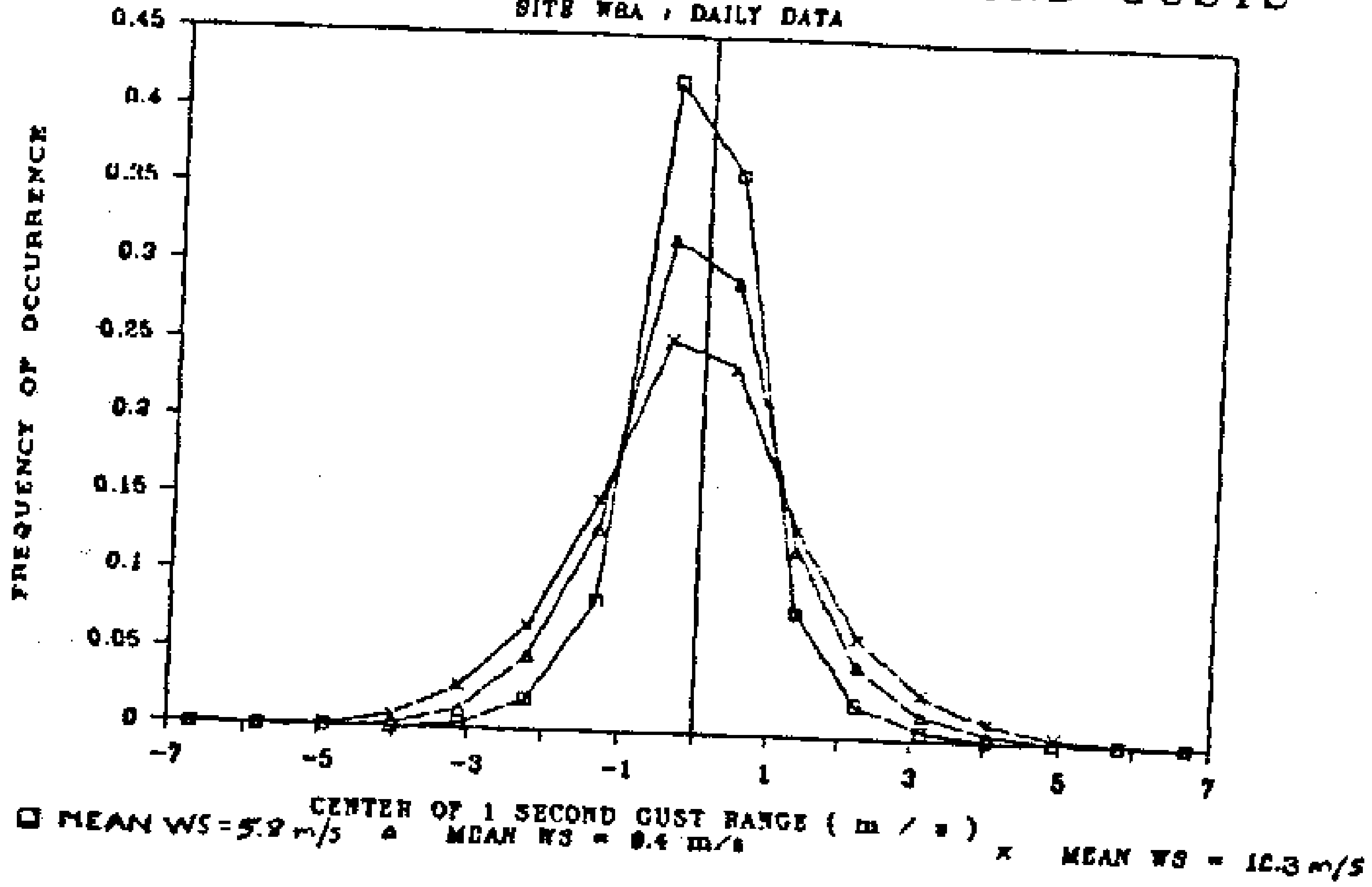


Figure 6.

PERCENT POWER INCREASE : MAX 1 SEC GUST

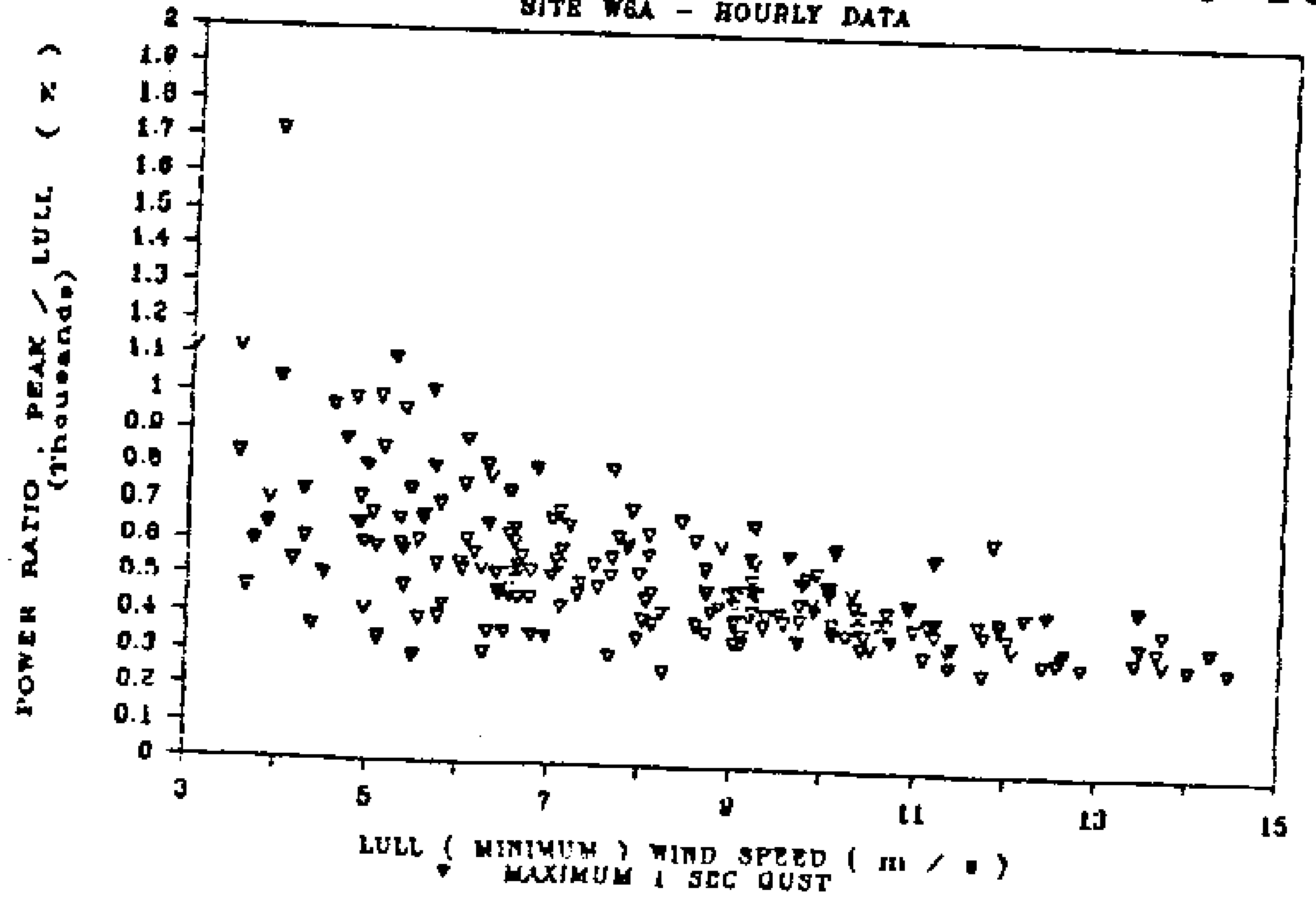
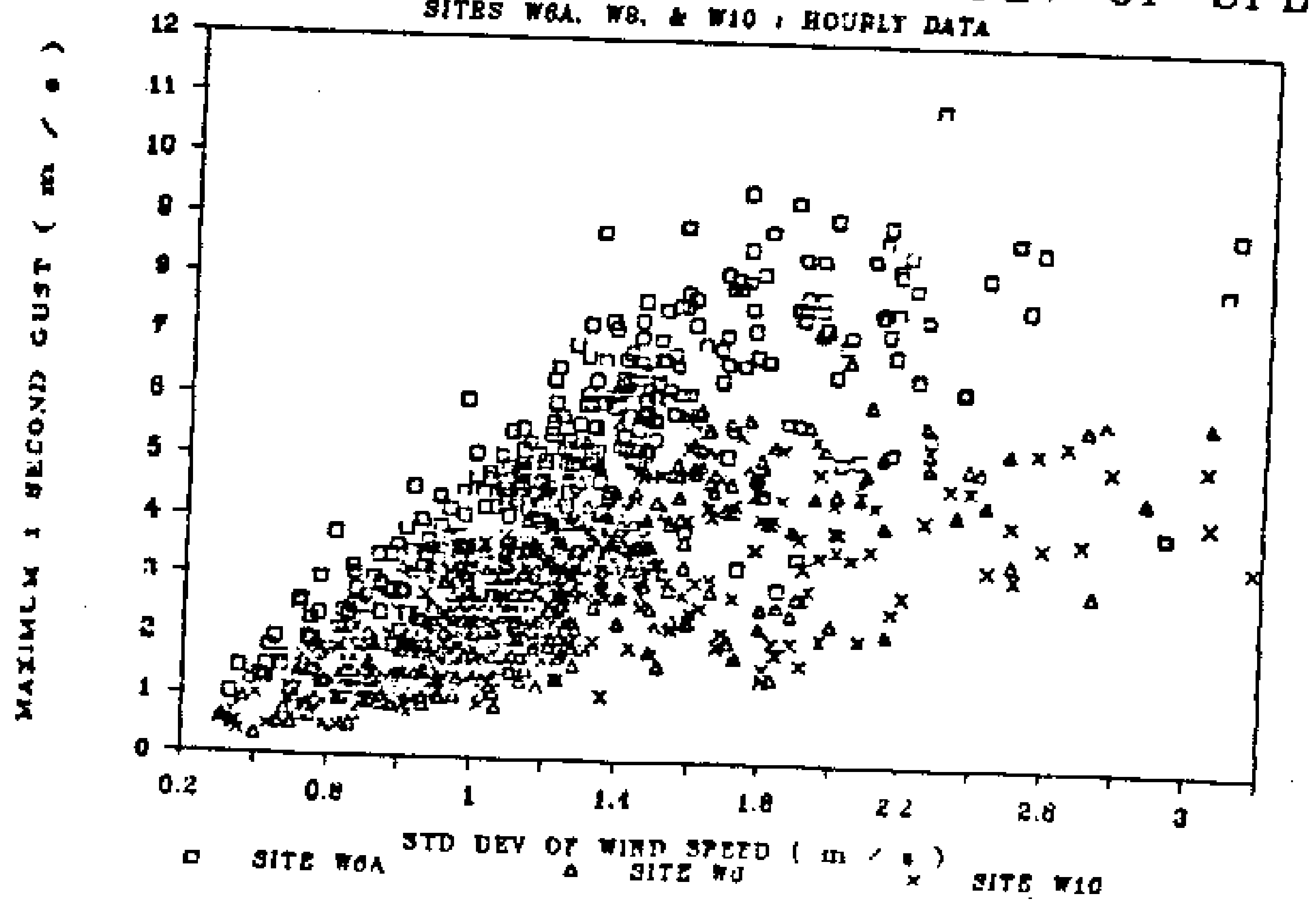


Figure 8.

MAXIMUM 1 SEC GUST VS STD DEV OF SPEED



relationships seen at site W6A absolute for all sites or are they site specific?

In some ways there is consistency between the two. As a basic comparator, the turbulence intensity versus wind speed at the two sites is quite similar, one to the other. Site WG has slightly higher mean TI than W6A by 6.5% for mean speeds > 6 m/s (13.4 mph). Mean gust magnitudes versus mean or standard deviation of wind speed at the two sites have nearly identical patterns. The same holds true for maximum 1-second gusts vs. mean or standard deviation of wind speed. In these analyses site WG does have a few extreme gusts of greater magnitude than the bulk of the values which fit the patterns displayed in Figure 5.

One way site WG does differ from site W6A is in hourly gust count versus mean and standard deviation of wind speed. Figure 3 shows this for site W6A. It turns out that at site WG, the gust count is almost constant, at approximately 1100 per hour for the range of wind speeds and standard deviations shown, but does show a slight increase with wind speed.

This presents a puzzling situation wherein some parameters show consistency between sites (gust magnitudes) yet the other (gust count) lacks consistency. The reasons for this may be related to the fact that the terrain upstream from the two sites is quite different. Site W6A is on an elongated hill and has fairly flat terrain immediately upstream. Site WG, on the other hand, is on a small hill downstream of a much taller hill (the one where W6A is located), with a dip in between. The extra terrain influence may contribute to the variance in gust nature. Both sites have turbines located upstream of them, although site W6A is much closer (6.5 RD) to them than site WG (10-12 RD). Could turbine wakes also be a factor in the nature of the turbulent fluctuations?

To determine to what extent turbine wake influences may contribute to the gustiness in the wind, hourly maximum 1-second gusts were recorded at two more sites in the wake test anemometer array. These additional sites were known as sites W8 (approximately 8.5 RD downstream from the I line of turbines) and W10 (approximately 10.5 RD downstream). If wake influences were a contributing factor to gustiness then one would expect to see a decrease in maximum gusts at locations further downstream from operating turbines, as the wakes decay. This appears to be the case, as comparison of concurrent hourly maximum positive one-second gusts vs. standard deviation of wind speed shows in Figure 8. (The pattern is similar when mean speed is used instead of standard deviation.) At these three sites the highest gust magnitudes are found at site W6A, lower values at W8 and lower values still at site W10.

The pattern is similar to what has already been observed, i.e., maximum one-second gusts increase with increasing mean or standard deviation of speed, but the rate of increase is lower at sites further downstream.

Recall that in comparing sites W6A and WG the rate of increase in gust magnitude with standard deviation of wind speed was, with a few exceptions, essentially identical. Also recall that site W6A is approximately 6.5 RD and WG is approximately 11 RD downstream from operating turbines. If gust characteristics are related to turbine wake influences, as the data from sites W6A, W8 and W10 imply, then one can conclude that the wake turbulence effects are very similar at sites W6A and WG, despite the fact that the distance to the nearest line of turbines is nearly doubled at site WG. What could be responsible for this?

It is hypothesized that the difference in elevation between site WG and the F line of turbines (WG is 53 meters (175 feet) lower at the maximum) inhibits the mixing of the free stream with the turbine wakes. Thus, the wake turbulence characteristics are preserved further downstream than would occur in flat terrain, which is essentially the situation at sites W6A, W8 and W10.

Horizontal Wind Shear Measurements

The previous discussion dealt with wind speed variability in time, but variations in space can also be important. As part of the wake turbulence monitoring program, two pairs of hub-height anemometer towers were erected, oriented cross-wind to the prevailing wind direction, with roughly one RD separation between the two. This allowed the measurement of horizontal wind shear, as the instrumentation from both towers in each pair was connected to a common 21X datalogger. One pair of anemometers was located at 2RD downstream from the I line of turbines (sites W2A and W2B), the other pair was at 6.5 RD downstream (sites W6A and W6B). Sampling at 1 Hz, instantaneous speed differences were recorded as daily binned frequency distributions. Maximum positive and negative wind shear were saved as well.

Figures 9 and 10 show daily frequency distributions of horizontal wind shear for several days with the highest mean speeds during the summer of 1988 at the 2 RD and 6.5 RD sites respectively. The mean speeds for the various days are printed below the graphs. The peculiar "tails" on the distributions at the W6 sites are due to the magnitude of the shear being underestimated from the outset. In the datalogger program, occurrences of values outside the limits of the bin sort range are counted in the last bin.

What is immediately obvious is that at the 2 RD sites there are more frequent occurrences of low shear, and some very

Figure 9.
HORIZONTAL WIND SPEED SHEAR (< 1 RD)

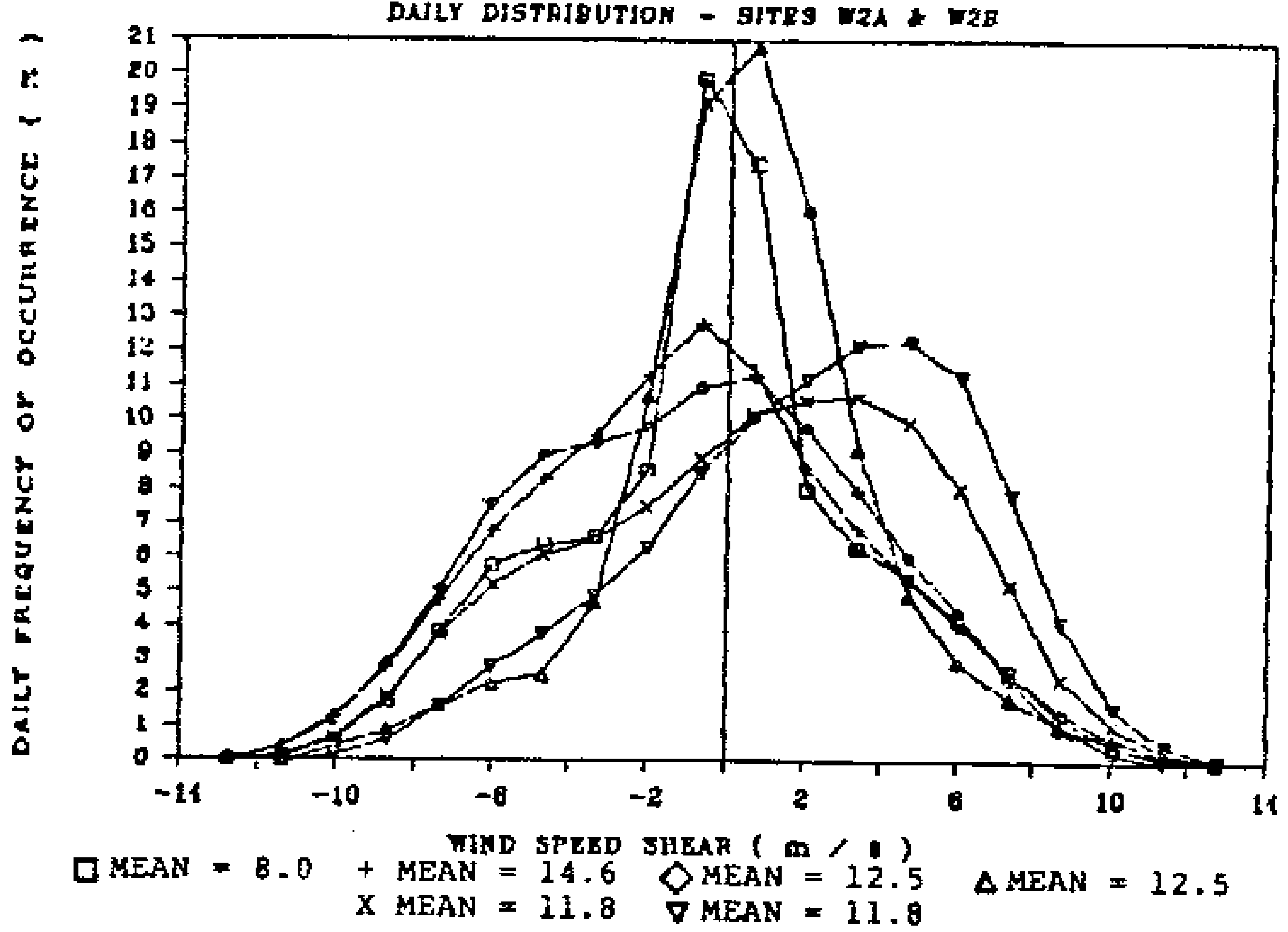


Figure 10.
HORIZONTAL WIND SPEED SHEAR (~1 RD)

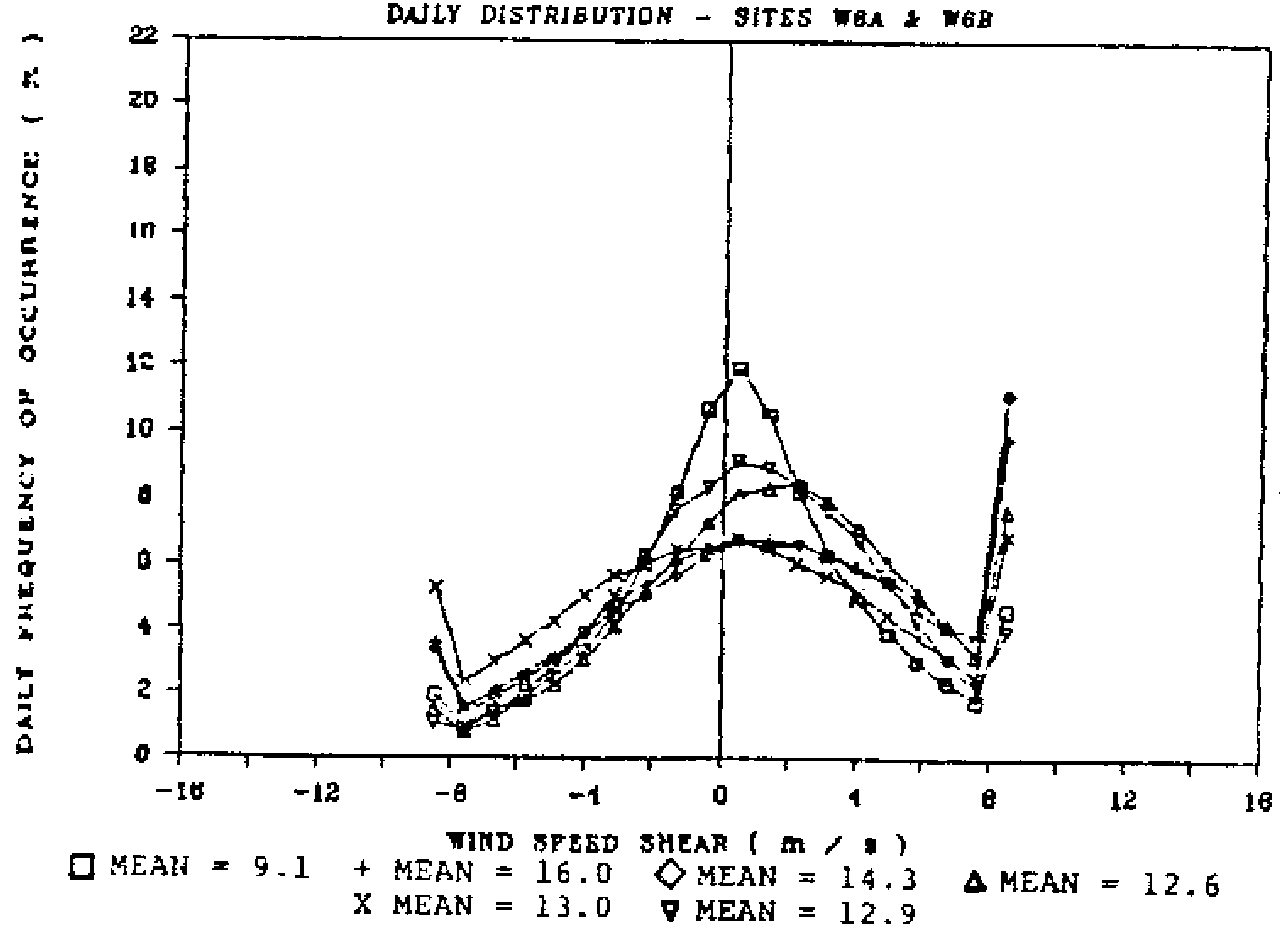


Figure 11.
DAILY MEAN SPEEDS AND SHEARS - SITE W2

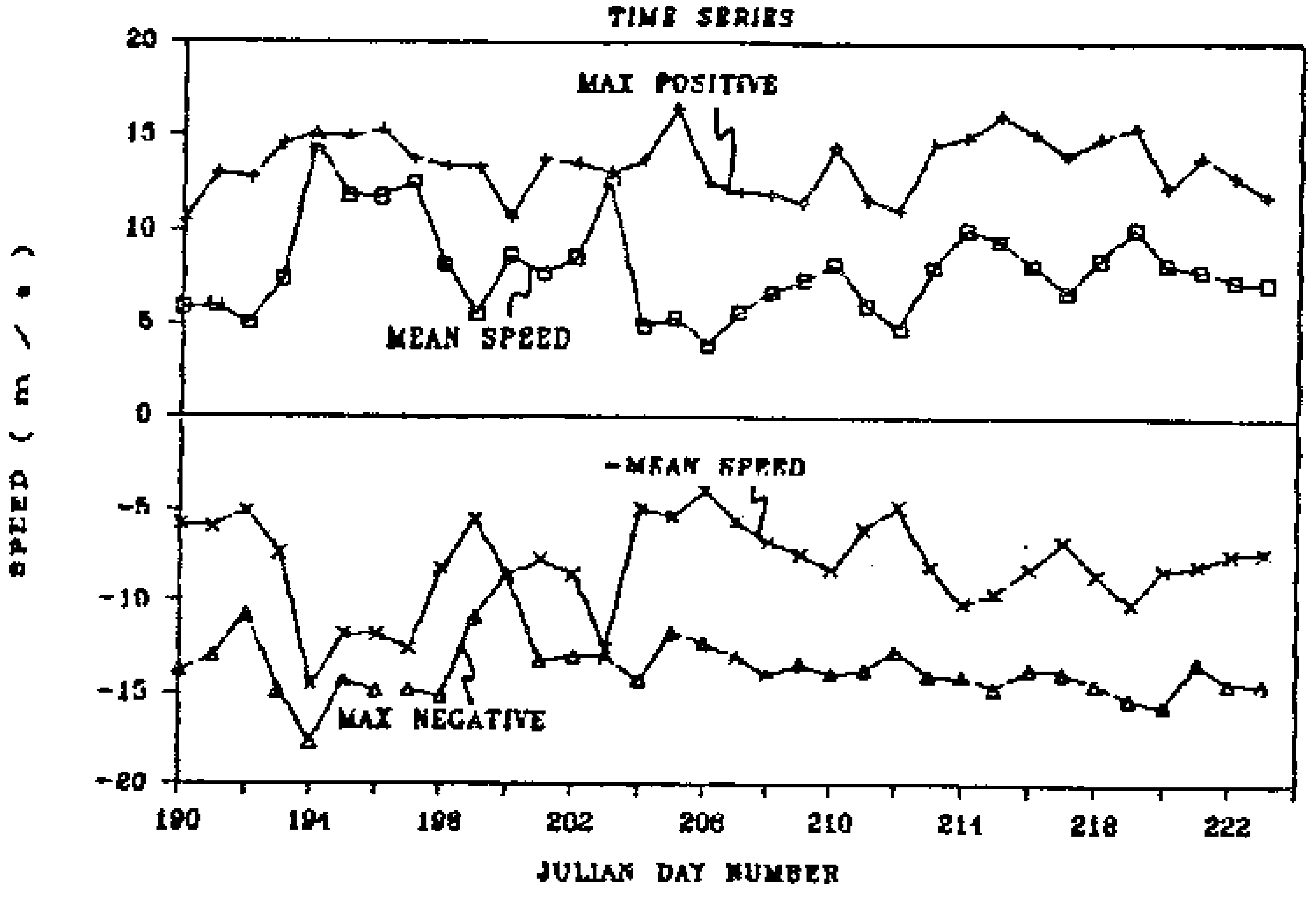
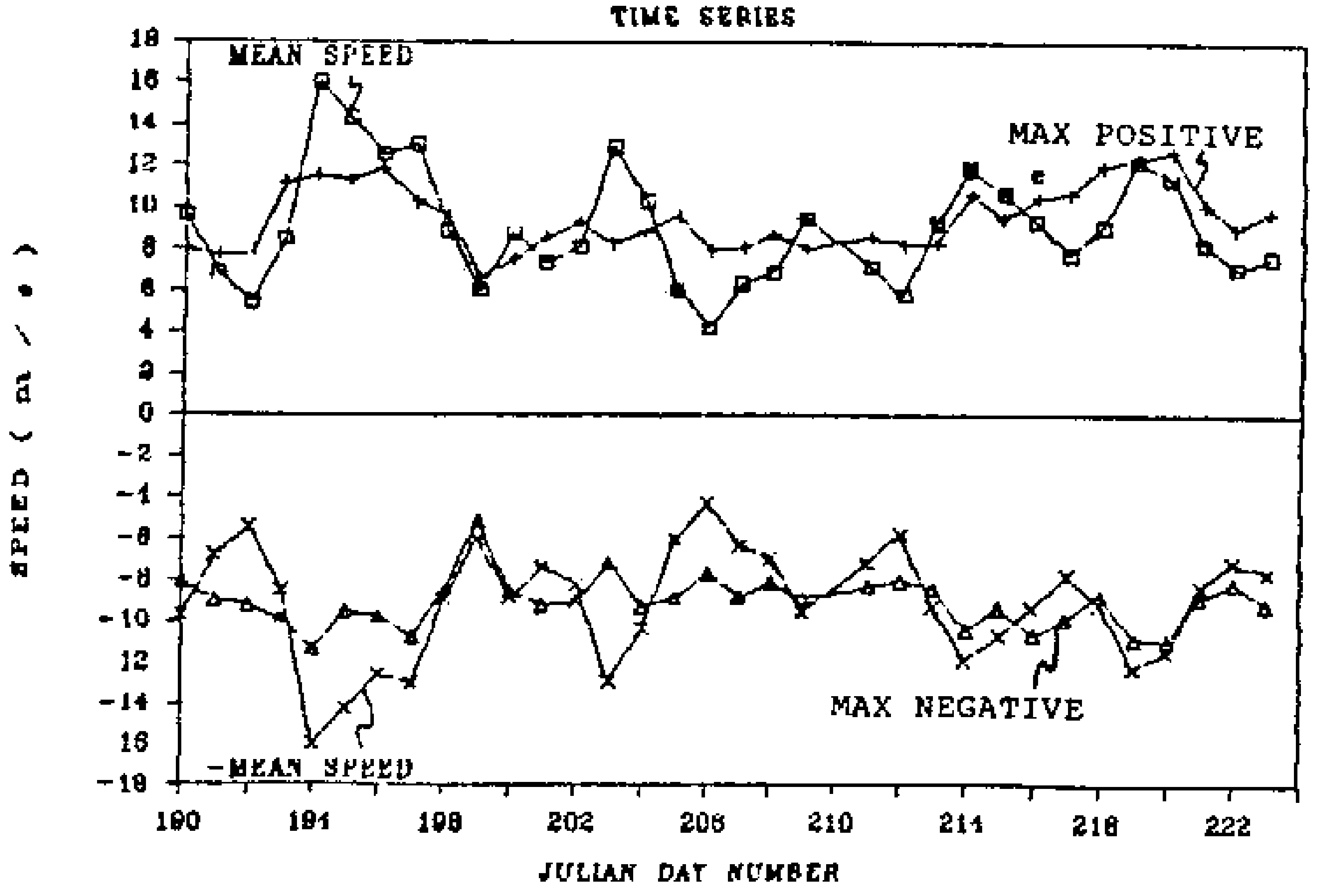


Figure 12.
DAILY MEAN SPEEDS AND SHEARS - SITE W6



high shears, as well. At this distance downstream, anemometers could either be both in a turbine wake (low shear) or one in a wake and one out (high shear). The distributions at the W6 sites is more regular and has fewer occurrences of low shears. The maximum shears are not as great at the 6.5 RD sites as at the 2 RD sites. Another pattern which can be seen is that, on the higher wind days, there is a wider range of shears measured, with lower frequency of weak shears and higher frequency of strong horizontal shears.

Extreme shears are more prevalent at the W2 (2 RD) sites as is evidenced by Figures 11 and 12. These are time series of daily mean speed and maximum positive and negative shears for the W2 and W6 sites respectively. The "A" tower sites are used as the reference for mean wind speed for both plots. The negative of the mean wind speed value is shown on the negative shear half of each graph, for reference.

These graphics show that, at 2 RD, maximum horizontal shears exceed the daily mean by a considerable margin whereas at 6.5 RD the maximum shears are virtually equal to the mean speeds.

The shear values could be important for operators who run turbines in winds parallel or nearly parallel to turbine rows. The imbalance on downstream turbine rotors could be severe at times. Turbines operating at low tip speed ratios would have reduced wake velocity deficits and therefore reduced shears. Still, it is difficult to determine what the shears may be without direct measurements.

Even at 6.5 RD there are shears of >10 m/s measured on almost a daily basis during the summer at these locations. It could be assumed that, based on the 2 RD and 6.5 RD data, horizontal shear distributions at points further downstream would continue to transform. Maximum shears may be reduced in magnitude but the shear frequency distributions are open to speculation.

Conclusions

Firm conclusions are difficult to define as the atmospheric boundary layer has such a high degree of randomness. Nonetheless, some general conclusions can be formed.

Based on the data presented here, both spacial and temporal fluctuations in the wind flow tend to increase in magnitude as mean speeds increase. There is also greater variability as absolute turbulence levels (standard deviation of wind speed) increase. Therefore, interpretation of turbulence, based on turbulence intensity, should be done with care, as this is a relative, not an absolute, term.