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Locator No: WQMS79-004
Contribution No: 79-004

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March 1979

Abstract

During the International Field Year on the Great Lakes (IFYGL) in 1972, the Canada Centre for Inland Waters maintained eleven meteorological buoys on the Great Lakes. The data from these buoys have found wide use although the accuracy of their measurements has been largely a matter of conjecture. The purpose of this paper is to evaluate the accuracy of these buoys by comparison of one buoy with a carefully instrumented fixed tower. In general the buoy measurements of wind speed, air and water temperature appear to be within design tolerances. The evaluation of relative humidity is inconclusive but newer sensors are now available and should be considered in any new buoy system design. The buoy wind direction measurements were severely degraded by vane oscillations induced by buoy motion. It is shown how the effect of these errors can be minimized by suitable averaging. Recommendations are given for improved wind direction sensing from small buoys. These include the use of the buoy itself as a direction sensor in strong and moderate winds.

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1. INTRODUCTION

During the International Field Year on the Great Lakes (IFYGL) in 1972, surface meteorological data was collected from a system of Canadian and U. S. small buoys. Such extensive continuous coverage of an enclosed water body is unique, and the resulting data base has been, and will continue to be, a valuable source of research and background data for limnological and meteorological studies. However, the value of this data base rests not only on its extensiveness, but also on its accuracy. Therefore, with a view towards establishing the accuracy of the Canadian (CCIW - IFYGL) meterological buoy system, one of the CCIW buoys (#4) was placed near a bottom-mounted tower during IFYGL (see Figure 1), in order to effect direct comparison of their measurements. The results of the comparison, over the 48 days of operation of the tower, are encouraging and have been known to some users at CCIW. However, the wide use, to which the buoy data has been and is being put, suggests that the results of the buoy/tower comparison should be more widely circulated.

2. PLATFORMS AND INSTRUMENTATION

Both buoy and tower systems have been described in detail elsewhere (Elder and Brady, 1972 and Donelan et al, 1974), and so a very brief description will suffice here. Figures 2 and 3 are photographs of the buoy and tower respectively. Anemometers and direction vanes are obvious in both photographs and the radiation shields - stacked pie plates on the buoy and vertical cylindrical vacuum bottles on the tower - house air temperature and humidity sensors. Table 1 lists the relevant similarities and differences of the buoy and tower sensors.

3. DATA

Both buoy and tower measurements were made at 10 minute intervals - the former, continuously from May to November; the latter, during four "intensive" boundary layer study periods: 20 to 27 May, 16 to 26 June, 18 August to 5 September and 3 to 15 October.

Thus, the comparisons were made during these "intensive" periods and then only when the wind direction was suitable for valid comparisons (see below). The 10 minute data were combined into hourly averages centered on the hour. Wind direction was averaged vectorially assuming a constant (unit) wind speed over the hour. Average wind speed was obtained in two ways: 1) a scalar average, i.e., wind direction ignored in the averaging; and 2) a vector average using the 10 minute east and north wind components, averaging them separately and recombining to obtain the magnitude of the average vector. Hereafter, "wind speed" means scalar averaged wind speed, unless otherwise stated. When a distinction between the two methods is being made "scalar wind speed" is used to denote the first form of averaging and "vector wind speed" denotes the second i.e., the magnitude of the average vector.

We have chosen to compare these buoy and tower data graphically and by means of linear regression. The comparisons are conveniently divided into four groups: 1) buoy versus tower measurements; 2) buoy measurements minus tower measurements versus tower wind speed; 3) scalar wind speed minus vector wind speed (both on the same platform) versus tower wind speed; 4) buoy measurements minus tower measurements as a function of time. The first of these groups includes all time coincident pairs of buoy and tower measurements in which the tower wind direction was outside the sector 170^0 to 220^0 true. (There were 854 of these pairs, 511 for humidity). Within this sector, the fixed tower instruments were downwind of the tower. The other three groups are designed to examine the differences between buoy and tower and, as such, are more sensitive to small differences arising because of real spatial differences in the measured variables. Thus, these three groups exclude both the short and rapidly changing fetches - i.e., the sector of 60^0 to 280^0 true (see Figure 4). There were 444 coincident pairs in the remaining wind directions except in the case of humidity, where there were 246 pairs. The tower humidity sensors were installed after the second intensive period.

Buoy wind direction, measured at 4.0 m was compared with tower wind direction at 14.5 m. Water temperature, measured in the same way on both platforms, was also compared directly.

Tower wind speed, temperature and humidity, however, were first interpolated to the appropriate buoy height, using the nearest valid tower measurements on either side. The interpolation was applied to the 10 minute data, and it was assumed that the interpolated variable varied with the logarithm of height between the two levels. Buoy wind speed, temperature and humidity were measured at 4.0, 3.6 and 3.6 metres respectively and tower measurements always bracketed these heights.

4. RESULTS

4.1 *Buoy Versus Tower*

The stability of the tower and the extreme care with which measurements were made allow us to regard its data set as a reference against which we can compare the buoy except in the case of relative humidity, in which calibration drifts of the tower sensors do not permit such a strong statement. In this case, inasmuch as the humidity sensors on buoy and tower were quite different, we can regard the differences between buoy and tower measurements as an upper limit to the error of either system. The results of the first group of comparisons - buoy versus tower - are shown in Figures 5, 6, 7, 8 and 9. The first three of these, figures 5, 6 and 7 attest to the accuracy of the buoy with regard to wind speed, temperature and water temperature. The correlation coefficients are within 1% of unity in all three cases and the slopes of the regression lines are within 1% of unity in the case wind speed and temperature and within 2% in the case of water temperature. This is seen to be quite remarkable when it is realized that the calibrations of buoy and tower sensors were entirely independent and in the case of wind speed employed quite different methods - individual wind tunnel calibration for the tower, but assumed common calibration with individual bearing friction tests for the buoy.

Further comparisons are explored in subsequent sections.

Figure 8 shows the buoy wind direction versus the tower wind direction. Although not as good as the previous three, the correlation coefficient and slope are respectably close to unity. Relative humidity (Figure 9) provides the least satisfying comparison but it is still apparent that buoy and tower sensors are yielding comparable values of relative humidity with the buoy tending to read lower than the tower.

4.2 *Buoy Minus Tower Versus Tower Wind Speed*

We have chosen to examine the error (buoy minus tower) in the buoy measurements against the wind speed for two reasons. First, the errors in the buoy measurements are probably due in large part to its motion either directly produced by the wind or, more importantly, caused by waves. Thus, in these plots, we have restricted the wind directions to those in which the fetch is moderate and slowly varying, so that the degree of buoy motion due to waves may be qualitatively related to the wind speed. Secondly, the errors in the buoy measurements acquire more significance the greater the wind speed, since the primary purpose in gathering buoy data was the lakewide estimation of momentum, heat and moisture transfers - themselves proportional to some power of the wind speed.

Figures 10, 11, 12, 13 and 14 are the differences between buoy and tower (corresponding to Figures 5, 6, 7, 8 and 9), versus tower wind speed. The corresponding statistics are summarized in Table 2. There is evidently no strong correlation of any of these differences with wind speed. Nevertheless, there are some interesting trends. The buoy's overestimate of wind speed shows a general, but very weak, reduction with increasing wind speed. There are several possible reasons for this: 1) tilt of anemometer due to buoy motion - up to 30^o; 2) reduction in mean height of anemometer due to buoy tilting; 3) sheltering of anemometer in large waves. Additional apparent wind run due to buoy rocking normal to the wind direction would tend to counteract these. Whatever the balance of causes, the overall result is that the buoy wind speed measurements are reliable in winds of up to 15 m/s and estimated waves of significant heights and periods up to 2.4 m and 7 s respectively. The waves were estimated from the empirical JONSWAP results (Hasselmann et al, 1973). On average (see Table 2), the buoy yielded wind speeds about 15 cm/s higher than the tower and the standard deviation of the error was 36 cm/s. Taking the differences to be normally distributed, this means that 90% of time the buoy was within + 74 cm/s to - 45 cm/s of the tower and only 10 (not plotted) or 2.2% of the 444 measurements were in error by more than 100 cm/s.

Air temperature and relative humidity show a general, but weak, trend with wind speed - air temperature positive and relative humidity negative. Although these change in the correct relative fashion to be both due to heating of the radiation shield, the change in relative humidity is some seven times too large to be accounted for by the observed change in temperature only. Therefore, a separate explanation is required for the trends in air temperature and relative humidity. There is insufficient evidence to define any particular cause or causes; nonetheless, we list some of the possible errors which could arise from the increased wind speed and the motion of the buoy: 1) increased aspiration; 2) increased internal solar insolation of the radiation shield; 3) reduced importance of radiant heating over convective cooling of radiation shield and recording package; 4) spray causing cooling and increased relative humidity; 5) lower average height of sensors due to buoy rocking. Water temperature also shows a small positive trend, but of the above possible sources of error only number 3) is applicable here.

In Figure 14 positive differences mean that buoy-measured wind direction is clockwise from that measured on the tower. It is clear that the wind direction error increases with wind speed, and at wind speeds above 8 m/s the westerly directions tend to be associated with a negative (counter clockwise) error, the easterly with a positive error, while the northerly directions are distributed on both sides of the zero line. Laboratory tests indicate that the construction of the compass is such that a steady tilt of the wind direction indicator would yield direction errors in the order of 0.3 degrees per degree of tilt - clearly not enough to account for the scatter in Figure 14. Normally, the standard deviation of the true wind direction over ten minutes is less than 10 degrees. These measurements are hourly averages of six instantaneous measurements, of a more or less normally distributed variable, so that the standard error of the mean would be $(< \frac{10}{\sqrt{6}} =)$ 4.1 degrees. We must conclude, therefore, that the very much larger differences and their dependence on wind direction are due to the dynamics of the wind direction sensor/compass/buoy/mooring complex activated by wind and waves. Further investigation of this is well outside the scope of this paper. However, we note that a cine film of the sensor-equipped buoy under the action of wind and waves would be very useful in resolving this question. In spite of the large scatter in Figure 14, we find (Table 2) that we may be reasonably confident of the hourly averaged buoy wind direction within -42° to 57°. It is worth mentioning that the apparent scatter in all the scatter plots is worse than that in the actual data, because the scatter plots were generated by line printer and each point may represent one or more data points. The chances of duplicate points occurring is greater, the greater the local density of points. Of course, all the calculations and regressions weighted each data point, plotted or not, equally.

4.3 *Scalar Minus Vector Wind Speed Versus Tower Wind Speed*

In view of the inaccuracy of the buoy wind direction sensing, we decided to examine the differences in hourly averaged wind speed computed vectorially or by the simple arithmetic average of the speed. Figure 15 shows the difference in the hourly averages of the tower wind speed averaged by the scalar and vector methods. The standard deviation of the difference is 11.7 cm/s and all but 14 or 3% of the points are within 20 cm/s. The mean value of the wind over all the points is 559 cm/s, from which it is easily shown that the average standard deviation of the six 10 minute wind directions from the hourly average is roughly* 12°. Since the tower wind direction sensor is heavily damped, almost all of this is due to variations with periods greater than 1 minute, and about one half due to fluctuations (i.e., periods of 1 minute to 1 hour) and one half to longer term (mesoscale) changes. These estimates are included to demonstrate that the real variations in wind direction over one hour are relatively small, on average. So that, with accurate sensors (Figure 15), it generally makes little difference whether scalar or vector averages are used in computing hourly averages.

*See section 5.2

Quite a different picture (Figure 16) emerges when the erratic behavior of the undamped instantaneously-sampled buoy-mounted wind direction sensor is added to the real variations in wind direction. Here we see that the scalar-vector differences are relatively large and distinctly dependent on wind speed - approaching values of 500 cm/s at the highest wind speeds measured (1459 cm/s). The standard deviation of the differences is 80.7 cm/s from which we infer that the standard deviation of the six 10 minute buoy measured wind directions from the hourly average is 31° - most of it due to buoy motion.

Clearly the buoy motion has severely degraded the wind direction data, which is unfortunate. However, the hourly averaged wind speed estimates need not suffer because of this, since the real differences between scalar and vector hourly averages are within the design, or achieved, buoy system wind speed accuracy.

4.4 *Buoy Minus Tower Versus Time*

The purpose of these figures (17, 18, 19 and 20) is to examine the changes in accuracy of the buoy measurements brought about by sensor changes. Figure 17, the wind speed differences versus time, shows no particular change in bias with change in sensor. Wind direction differences (Figure 18), on the other hand, seem to be biased negatively after the installation of the last sensor. However, on closer inspection we see that the bias is due to westerly winds. As we have seen (Figure 14), stong westerly winds tend to produce a negative bias, and the average wind speed was higher in October than any of the other months shown.

Air and water temperature differences (Figures 19 and 20) show a positive bias in part of the month of June. This does not appear to be due to the sensor change since the anamolous section runs from 20th to the 24th, only 1/3 of the comparison time of that sensor. This anamalous period coincides with the highest rate of solar insolation and with the passage of Hurricane Agnes. June is also the month of strongest nearshore surface temperature gradients as the lake warms from the edges inward. In addition the Niagara River water may have quite a different temperature from the lake near the mouth at this time of year. It would seem that there is little reason to consider the differences in sensors as a significant source of error.

Relative humidity sensors were not installed on the tower until August, and, as a result, the short comparison period does not reveal any useful information regarding the change of buoy sensors.

In general, it appears that the variability among the sensors introduces an uncertainty which is negligible compared to the other sources of error. This should be expected as all sensors were subjected to the same calibration procedures before use.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1

The above comparison of the CCIW - IFYGL meteorological buoy system with the CCIW - IFYGL profile tower system leads to the following conclusions. Wind speed, air temperature and water temperature are recoverable with acceptable accuracy for most uses for which the buoy system was designed. Relative humidity needs significant improvement, if it is to be useful in the calculation of evaporation and latent heat transfers. Since the buoys were designed, new sensors have become available and they should be evaluated for use on the buoys.

Our findings regarding the large errors in direction sensing are borne out by an earlier evaluation (Taylor, 1972), in which he states that: "Field *visual* observations have shown that the wind vane is most stable at speeds between 5 kts. and 15 kts. (2.6 and 7.7 m/s). At speeds above that, the buoy is in greater motion (higher waves) and the vane tends to whip ±*30* degrees from the mean"*.

It seems apparent that very careful mechanical design or a quite different approach to the future measurement of wind direction is required. In the meantime, what is the best approach to using the CCIW - IFYGL meteorological buoy data?

5.2 *Recommendation for Usage of CCIW - IFYGL Meteorological Buoy Data*

We recommend that air temperature, water temperature and relative humidity be used as supplied with the confidence implied by Table 2.

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* The italics are ours.

Users for whom wind speed is appropriate (evaporation, heat flux etc.) should, of course, deal with the scalar average over the period appropriate to their study. Users requiring the vector wind should use the scalar average wind speed over average periods up to x hours, where x is to be determined below.

Let the real rate of change (steady trend) of wind direction be y degrees per hour, so that over the averaging period x, the wind direction oscillates about the trend line $\bar{\theta} - \frac{yx}{2}$ to $\bar{\theta} + \frac{yx}{2}$; where $\bar{\theta}$ is the true mean wind direction over the averaging period x hours. Some of these shorter term oscillations are due to real wind fluctuations of periods greater than the Nyquist period (20 minutes) σ_u; others are due to periods shorter than this σ_w; and still others are due to the erratic behaviour of the wind vane σ_v, caused mostly by buoy motion due to waves. These last two σ_w and σ_v are badly aliased and as a result may contribute to very long period fluctuations.

Thus the total variance of the buoy-measured wind direction $\sigma_b^2 = \sigma_u^2 + \sigma_T^2 + \sigma_v^2 + \sigma_w^2$, whereas that of the tower-measured wind direction $\sigma_t^2 = \sigma_u^2 + \sigma_T^2 + \sigma_w^2$; where σ_T^2 is the variance caused by the linear trend of y°/hour. It is easily shown that for cases in which the interval x is centered on a measurement:

$$\sigma_T^2 \begin{cases} = \dfrac{y^2x^2}{12} \left(1 - \dfrac{1}{f_s^2\, x^2}\right) & f_s\, x \text{ odd} \\ \doteq \dfrac{y^2x^2}{12} \left(1 + \dfrac{2}{f_s^2\, x^2}\right) & f_s\, x \text{ even} \end{cases} \qquad (5.2.1)$$

where f_s is the sampling frequency in samples per hour.

In the present context, the following queries are relevant. Given a wind measuring system in which the speed sensor is "perfect" and the direction sensor "noisy", what is the best strategy for 1) the estimation of the magnitude of the vector wind, and 2) the resolution of steady wind direction trends.

We note that for a steady wind speed W and an unskewed distribution of wind direction deviations θ' from the mean $\overline{\theta}$, the difference between scalar and vector magnitudes is given by:

$$\Delta W = W (1 - \overline{\cos \theta'}) \qquad (5.2.2)$$

Which, for angles, θ', less than 60° is closely approximated by:

$$\frac{\Delta W}{W} = \left(\frac{\pi}{180}\right)^2 \frac{\overline{\theta'^2}}{2} = 1.52 \times 10^{-4} \sigma_\theta^{\,2} \qquad (5.2.3)$$

We remark that it is not necessary to assume that the wind speed is steady, but only that θ and W are independent. In the case of unsteady winds, W is replaced by $\overline{W}$. Clearly the percentage error in the vector wind is optimized by minimizing $\sigma_\theta^{\,2}$, that is, designing the system so that σ_V is very small (good tracking) and σ_W is reduced (good damping). However, neither of these is possible after the fact, and so the only option left is the separate averaging of the wind direction measurements to reduce the standard error of the mean, before computing the vector wind.

The correct estimate of vector magnitude is achieved when the averaging time is chosen such that the standard deviation of the error in the buoy wind direction measurements equals the real standard deviation of the wind at periods between the chosen averaging time and the original Nyquist sampling interval. That is, the error remaining after averaging compensates for the loss of real wind variance due to averaging.

The effects of aliasing are demonstrated in Figure 21 on an arbitrary f^{-2} spectrum of wind direction fluctuations. The tower wind direction sensor is heavily damped and probably insensitive to fluctuations above about 0.01 Hertz. It is, of course, not affected by waves. The buoy wind direction vane, on the other hand, is undamped and, although the compass is damped to some extent, the large fluctuations of the vane due to wave motion of the buoy contribute to the 'noise' in the wind direction estimates from the buoy. In both cases (buoy and tower) the sampling frequency fs is 6 times per hour with a Nyquist frequency f_n of 3 per hour. Consequently, there is a great deal of aliasing, or folding, of the variance of wind direction estimates at frequencies above f_n into the range of frequencies 0 to f_n. In the case of the tower, the aliasing contributes somewhat to the spectrum in the region of 0 to f_n whereas, the buoy measurements are very seriously aliased by the short term fluctuations and, in addition, motion of the buoy due to waves may contribute significantly to the aliasing problem.

In both cases, then, the apparent variance in the frequency range of 0 to f_n has been increased through aliasing. The degree to which this is so is reflected in the difference between scalar and vector wind speed estimates. Using the scalar/vector differences over 6 ten minute readings and (5.2.3), we found that the apparent standard deviation of wind direction in the frequency range between 0.5 cycles per hour and 3 cycles per hour was 31° for the buoy and 12° for the tower. Some of the measured variance is caused by a trend in the wind direction, since much of the data used would have been gathered during shifting winds. The choice of an appropriate value of the trend parameter y is somewhat arbitrary, but it is unlikely to be bigger on average than 15°/hour, which is the trend associated with purely diurnal rotation associated with land and sea breezes. Large pressure systems would tend to reduce this value, while squall lines and other lake storms would tend to increase it. Using this value (y=15°/hour) for our case of x = 1 hour and f_s = 6/hour, we find σ_T = 4.4°. Therefore, removing the effect of trend σ_T , we find for the buoy $(\sigma_b^2 - \sigma_T^2)^{\frac{1}{2}}$ = 30.7° and for the tower $(\sigma_t^2 - \sigma_T^2)^{\frac{1}{2}}$ = 11.1°. Now the intensity of lateral turbulent fluctuations about a steady wind $\frac{\sigma_\ell}{U}$ in this frequency range is typically about 0.8 to 1.2 which corresponds to values of σ_θ of 4.6° to 6.9°. Clearly the aliasing of both sensors has produced a significant increase in the apparent variance of wind direction and consequently an underestimate of the magnitude of the vector wind. If we take a typical value of σ_θ of 5.7° we see that the variance has been increased by a factor of 29.0 for the buoy and 3.8 for the tower. To improve our estimates of the magnitude of the vector wind, we need to reduce the variability of the wind direction estimates before applying them in the computation of the vector wind. This can be done most simply by averaging the wind direction estimates over a time such that the reduced variance approximates the expected variance of $(5.7°)^2$.

The most simple form of averaging appropriate to this problem is that of taking a running mean over x hours. Figure 22 contains the corresponding squared filter function, $\frac{\sin^2 \pi f x}{\pi^2 f^2 x^2}$. For simplicity we will approximate the aliased wind direction spectrum in the frequency range of 0 to f_n by a white (constant) spectrum of unity amplitude. The total variance of this aliased normalized spectrum is therefore f_n. The reduced variance of the filtered spectrum is given to a good approximation by

$$\int_0^\infty \frac{\sin^2 \pi f x}{\pi^2 f^2 x^2} df = \frac{1}{2x}.$$ The variance is therefore reduced by the factor $\frac{1}{2xf_n}$. In our case, f_n is 3 cycles per hour. Therefore in order to reduce the variance of the wind direction estimates about a linear trend to $(5.7)^2$ we need to apply a running mean filter over $\frac{29.0}{6} = 4.8$ hours for the buoy and $\frac{3.8}{6} = 0.6$ hours for the tower.

The percentage underestimate of the computed vector magnitude may be estimated directly from a modified form of (5.2.3):

$$100 \times \frac{\Delta w}{w} = 1.52 \times 10^{-2} \left(\frac{\sigma^2 - \sigma_T^2}{2x\ f_n} - \sigma_u^2 \right) \% \qquad (5.2.4)$$

where $\sigma = \sigma_b$ (buoy) or σ_t (tower).

In our case f_n is 3 cycles per hour and we have estimated typical values of σ_u and σ_T of 5.7° and 4.4° respectively. Thus we may tabulate (Table 3) values of $\frac{\Delta w}{w} \times 100$ for various values of the running mean span x. It can be seen that use of the raw (10 minute) buoy wind direction data can lead to a 13.5% underestimate of the hourly averaged vector magnitude or a 29% underestimate of the wind stress. The application of a running mean filter over an hour reduces the underestimate to less than 2%, and little is to be gained by using a broader filter. The tower data, on the other hand, may be used in the raw state since an improvement of one per cent or so probably does not justify the computational effort of applying a filter.

Clearly then, the CCIW-IFYGL buoy wind direction estimates should be separately averaged (scalar wind speed, unit vector average of direction) for 1 to 3 hours. Longer averaging times do not reduce the standard error of the direction estimates appreciably, and can cause a serious over-estimate of the vector magnitude if the wind direction is changing systematically. Vector magnitudes, computed after separate averaging of speed and direction, may be corrected using Table 3.

5.3 *Recommendations for Improvement to the CCIW-IFYGL Meteorological Buoy System*

Improvements to the wind direction and humidity sensors are clearly required. Improvements in humidity sensing can be achieved only through the development and evaluation of improved humidity transducers. Wind direction sensing, on the other hand, may be dramatically improved by using a different approach with existing or conceived sensors.

(i) The use of a large vane to orient the buoy with respect to the wind makes the buoy itself a far better wind direction sensor than its poorly damped vane for all but light wind conditions. Since stronger winds are more important for most purposes, we would have been better off to have placed the compass directly on the buoy, thereby using its inertia to reduce the aliasing problem inherent in the infrequent instantaneous direction samples provided by the Plessey clamped compass.

(ii) A low powered compass, which is capable of providing an averaged direction reading, would completely eliminate the aliasing problem described above. Such a compass is described by Donelan (1977).

(iii) Suggestion (i) or (ii) above yields the direction of the buoy, which may be in error in light winds. The wind direction with respect to the buoy may be extracted from two propeller anemometers with their axes horizontal and pointed at + and - 45° degrees to the "upwind" side of the buoy. The true average wind runs of these two propellers would yield wind direction estimates with respect to the buoy, which would be virtually unaffected by the motion of the buoy. A cup anemometer would still be required for the wind speed, since buoy motion would have a greater effect on the speed estimates produced by propellers.

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TABLE 1: Summary of Buoy and Tower Systems

	BUOY	TOWER
Recorder	Plessey Hymet Model MM-1	Plessey Hymet Model MM-6
Sampling Rate	10-minute Interval	10-minute Interval
Temperature Range	-10°C to +40°C	-10°C to + 40°C
Recorder Accuracy	±1 part in 1024	±1 part in 1024
{Wind Speed Anemometer	3-cup Beckman and Whitley Model 170-41	3-cup R. M. Young Special Model
Sampling Period	10-minute wind run	10-minute wind run
Starting Speed	45-90 cm/s	32 cm/s
Stopping Speed	45-90 cm/s	25 cm/s
Accuracy	±2% above 200 cm/s	±2 cm/s
Wind Direction Sensor	Single, flat plate vane coupled to an oil-damped magnetic compass	Single, flat plate vane coupled to a potentiometer. Heavily oil-damped.
Accuracy	±5 degrees	±2 degrees
Air Temperature Sensor	YSI thermistor No. 44005	YSI thermistor No. 44030
Range	-10 to +40°C	0 to 35°C
Time Constant	30 sec without radiation shield	1.5 minutes
Accuracy	±0.1°C	±0.08°C
Exposure	Naturally aspirated Thaller-type radiation shield	Gill fan-aspirated radiation shield
Water Temperature Sensor	YSI Thermistor No. 44030	YSI Thermistor No. 44030
Range	-2 to +35°C	0 to 35°C
Time Constant	Approximately 5 minutes	5 minutes
Accuracy	±0.1°C	±0.08°C
{Relative Humidity Sensor	Hydrodynamics Transducer Model 15-7012	Sangamo Ltd. radiosonde carbon hydristor
Range	40 to 99%	40 to 100%
Time Constant	5 minutes	1 minute
Accuracy	±3%	±5%
Exposure	Naturally aspirated Thaller-type radiation shield	Gill fan-aspirated radiation shield

TABLE 2: Summary of Buoy and Tower Hourly Averages

PARAMETER	UNITS	NO. OF POINTS	BUOY RANGE MIN.	BUOY RANGE MAX.	BUOY MEAN	BUOY STD. DEV.	TOWER RANGE MIN.	TOWER RANGE MAX.	TOWER MEAN	TOWER STD. DEV.	DIFFERENCES (BUOY-TOWER) NO. OF POINTS	DIFFERENCES RANGE MIN.	DIFFERENCES RANGE MAX.	DIFFERENCES MEAN	DIFFERENCES STD. DEV.
Wind Speed	cm/s	852	0	1499.5	510.9	310.7	21.2	1458.6	499.7	311.1	444	-172.9	202.0	14.5	36.0
Wind Direction	degrees	854	0	360	185	119	0	360	178	120	444	-162.8	172.1	7.5	29.9
Air Temperature	°C	854	4.7	25.8	15.2	4.9	4.9	25.0	15.1	4.9	444	-1.3	3.1	0.15	0.36
Water Temperature	°C	854	8.2	24.0	16.3	4.3	8.0	23.7	16.2	4.3	444	-2.5	1.6	0.04	0.46
Relative Humidity	%	511	42.5	92.9	74.4	12.0	39.4	97.7	79.8	13.1	246	-21.5	8.6	-4.8	6.2

Table 3. Percentage Under-estimate of the hourly averaged vector magnitude as a function of the running mean span

Running mean span x	$\frac{\Delta w}{w} \times 100$	$\frac{\Delta w}{w} \times 100$
	Tower	Buoy
hours	%	%
1/6	1.38	13.5
1/3	0.44	6.5
1/2	0.13	4.2
1	-0.18	1.8
2		0.68
3		0.29
4		0.09
5		-0.03

FIGURE CAPTIONS

1. Lake Ontario showing the disposition of the CCIW-IFYGL meteorological buoys and the CCIW-IFYGL profile tower.
2. Photograph of the CCIW-IFYGL meteorological buoy.
3. Photograph of the CCIW-IFYGL profile tower.
4. The distribution of fetch distances with bearing from the Niagara Bar site of the CCIW-IFYGL profile tower. Also shown are the excluded data, based on wind direction, in the following figures.
5. Scatter diagram and least squares regression line of buoy wind speed versus tower wind speed. Wind directions in which the tower may have shaded its sensors (170° to 220°) are excluded, leaving 854 hourly average points for comparison. The correlation coefficient 'r', slope 'm' and intercept 'c' are indicated.
6. As in 5, but for air temperature.
7. As in 5, but for water temperature.
8. As in 5, but for wind direction.
9. As in 5, but for relative humidity. Here there are only 511 hourly average points, because the humidity sensors on the tower were installed mid-way through the tests.
10. Scatter diagram of buoy wind speed minus tower wind speed versus tower wind speed. Wind directions in which the fetch is very short or very direction dependent are excluded, leaving 444 hourly average points for comparison.

11. As in 10, but for air temperature.

12. As in 10, but for relative humidity. Here there are only 246 hourly average points, because the humidity sensors on the tower were installed mid-way through the tests.

13. As in 10, but for water temperature.

14. As in 10, but for wind direction. Symbols are used to differentiate between tower wind directions of west (280^{o} to 315^{o}), North (315^{o} to 45^{o}) and east (45^{o} to 60^{o}).

15. As in 10, but for the difference between tower scalar averaged wind speed and tower vector averaged wind speed.

16. As in 10, but for the difference between buoy scalar averaged wind speed and buoy vector averaged wind speed. The least squares regression line is also shown.

17. Scatter diagram of buoy wind speed minus tower wind speed versus time. Wind directions in which the fetch is very short or very direction dependent are excluded, leaving 444 hourly average points for comparison. The dates of buoy sensor changes are also shown.

18. As in 17, but for wind direction.

19. As in 17, but for air temperature.

20. As in 17, but for water temperature.

21. Schematic of the effects of aliasing of the wind direction estimates.

22. Aliased wind direction spectrum (assumed white) and the squared running mean filter function over x hours. In this figure x = 1 hour.

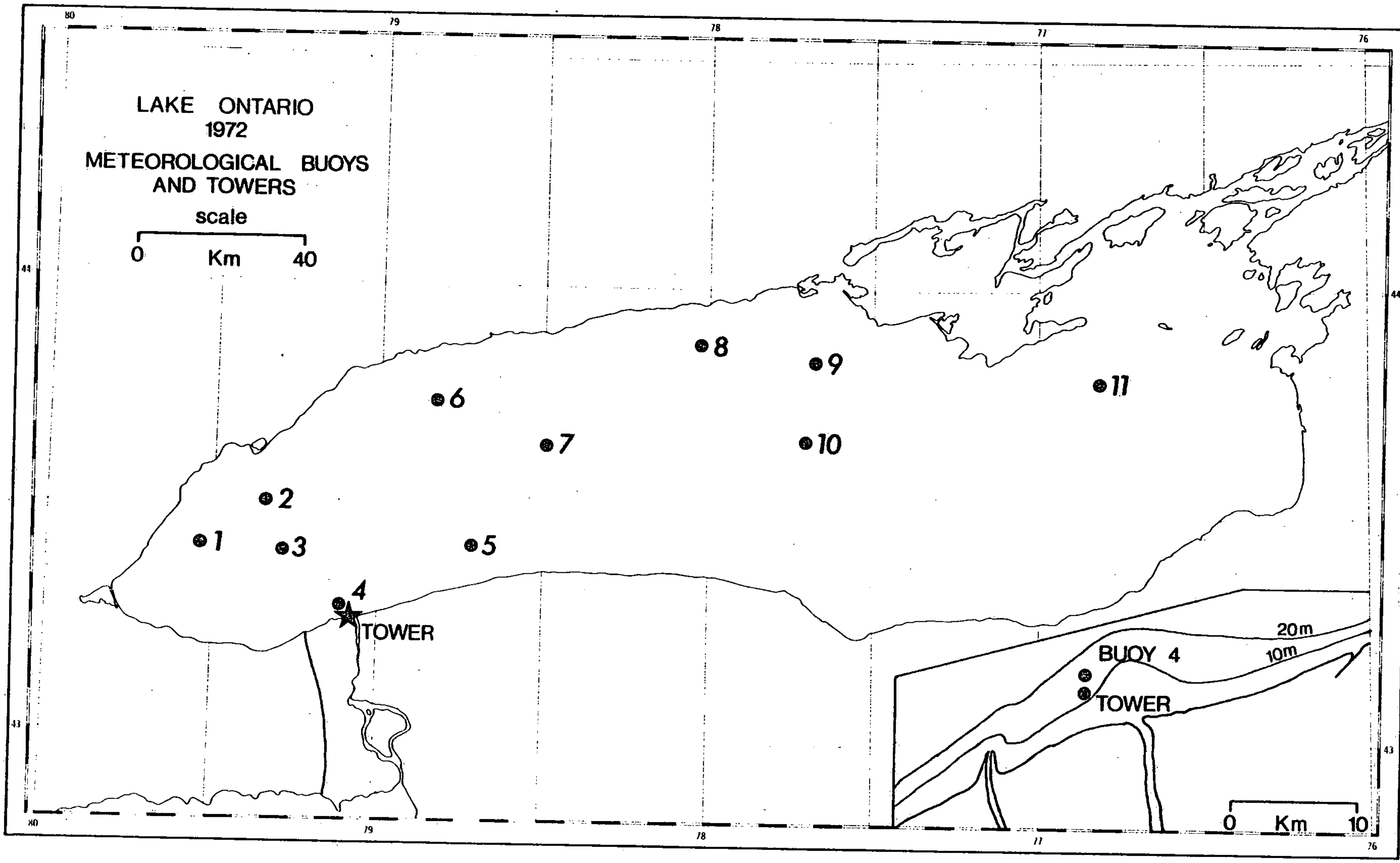

LAKE ONTARIO
1972
METEOROLOGICAL BUOYS
AND TOWERS
scale
0 Km 40
1
2
3
4
5
6
7
8
9
10
11
TOWER
BUOY 4
TOWER
20m
10m
0 Km 10
80
79
78
77
76
44
43

Figure I

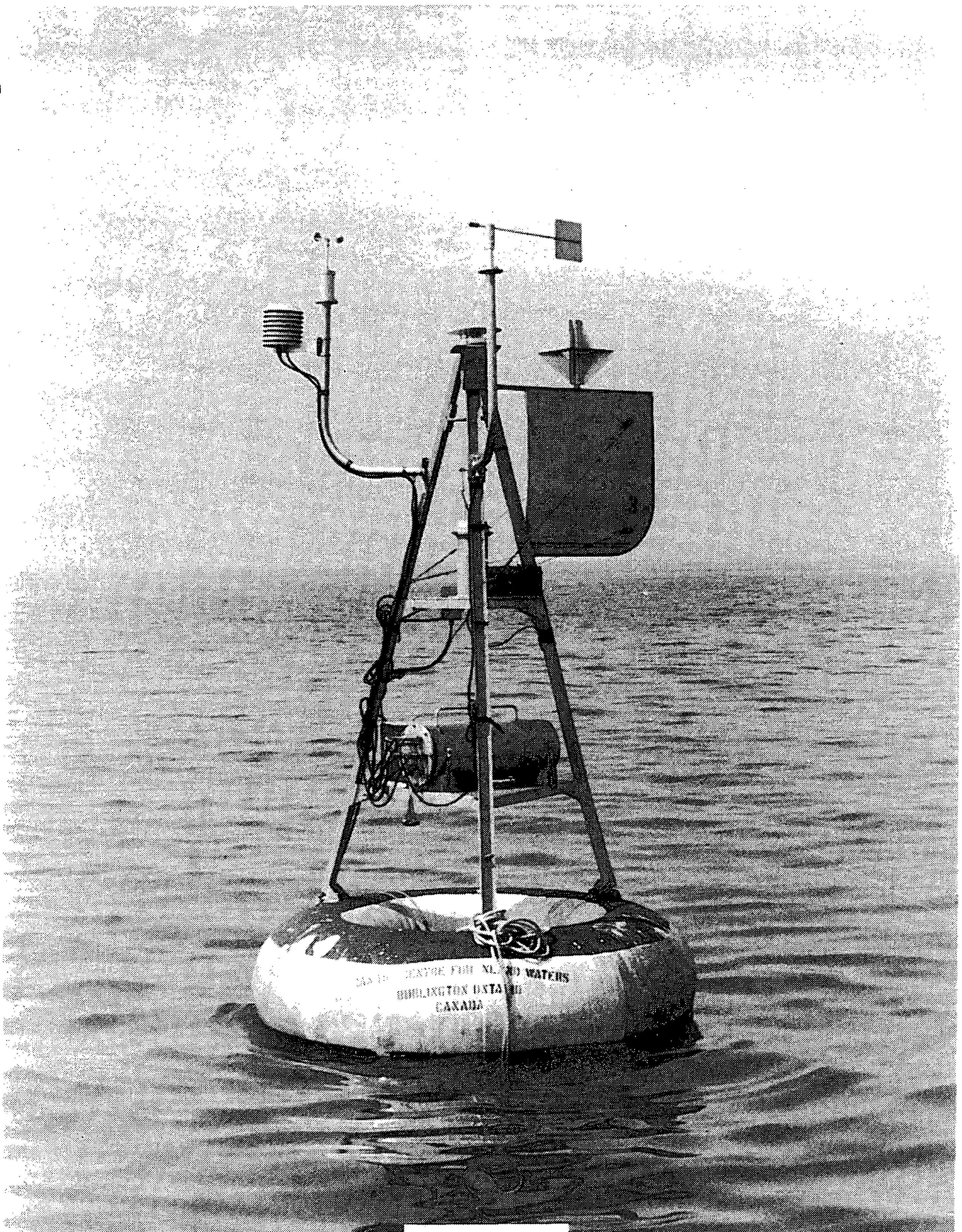


Figure 2

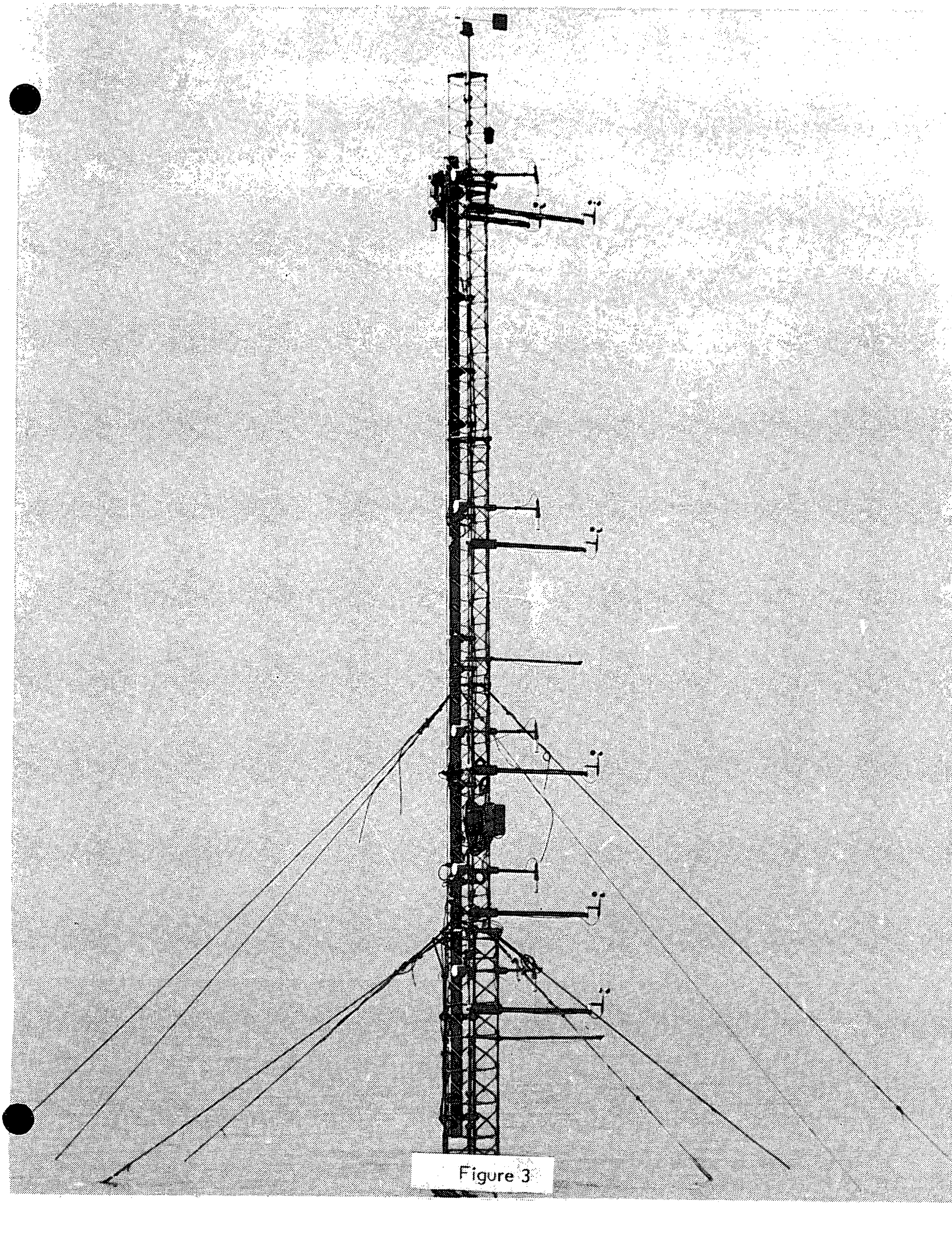
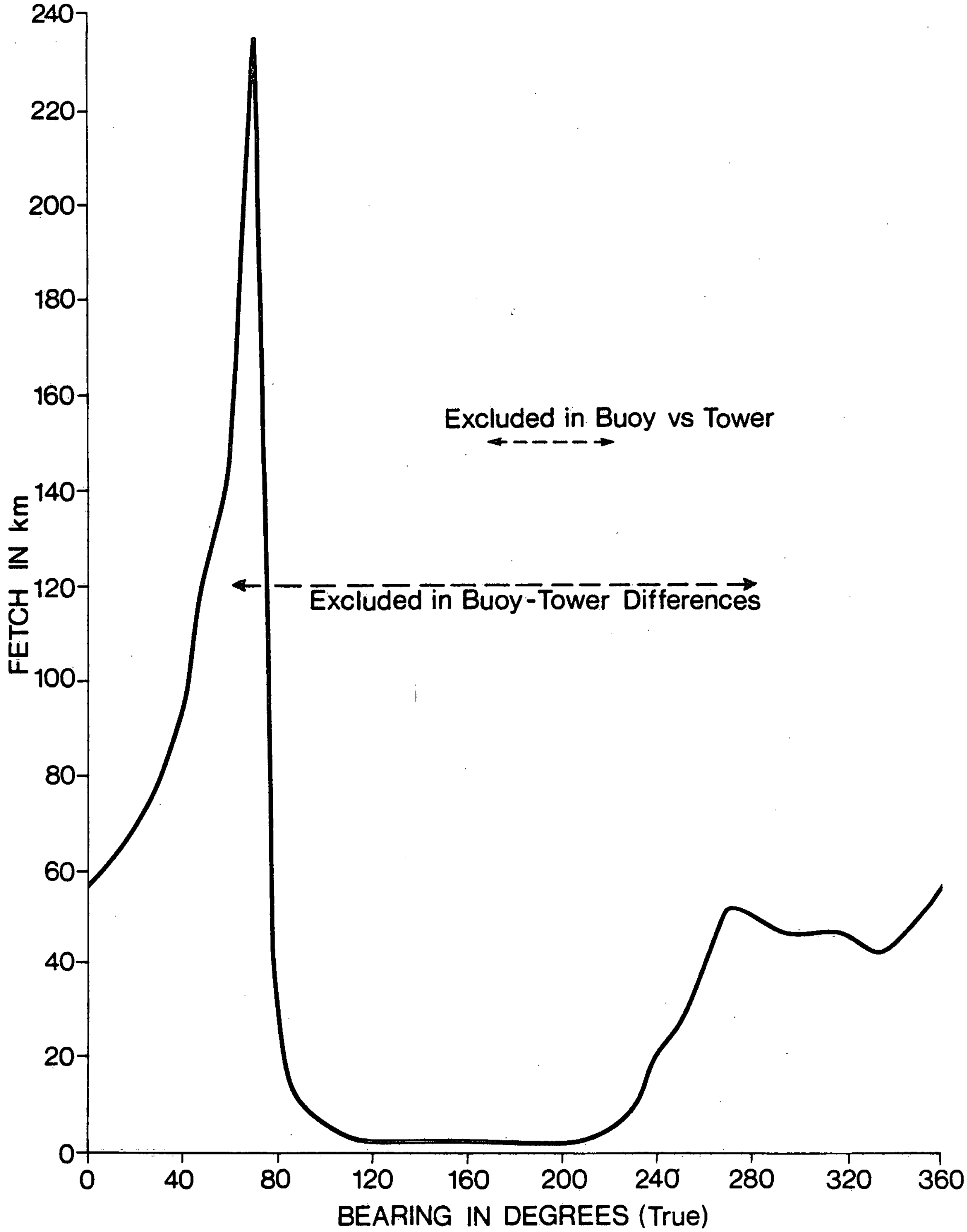


Figure 3



LAKE ONTARIO FETCH vs BEARING, 1972 NIAGARA BAR TOWER

Figure 4

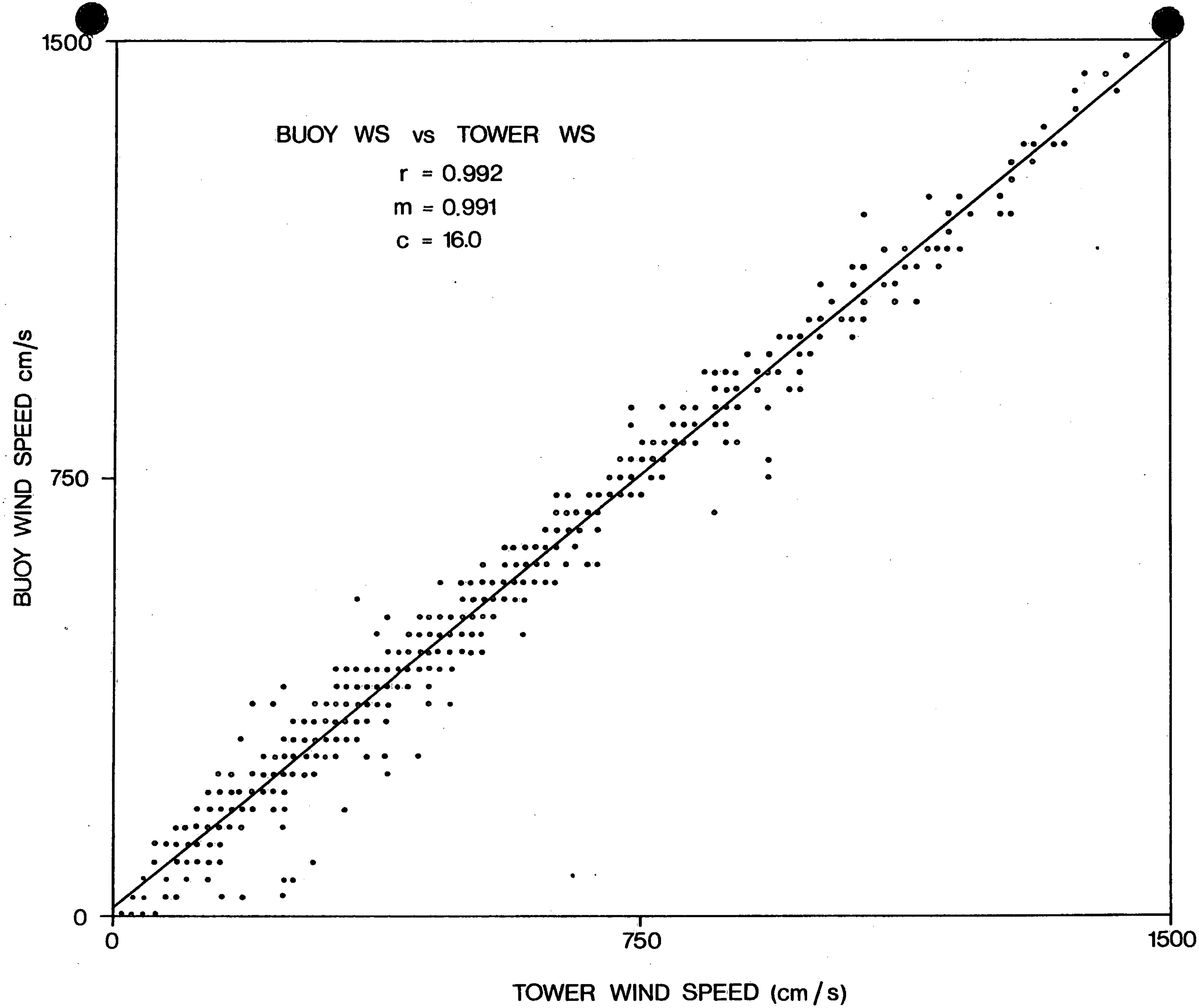
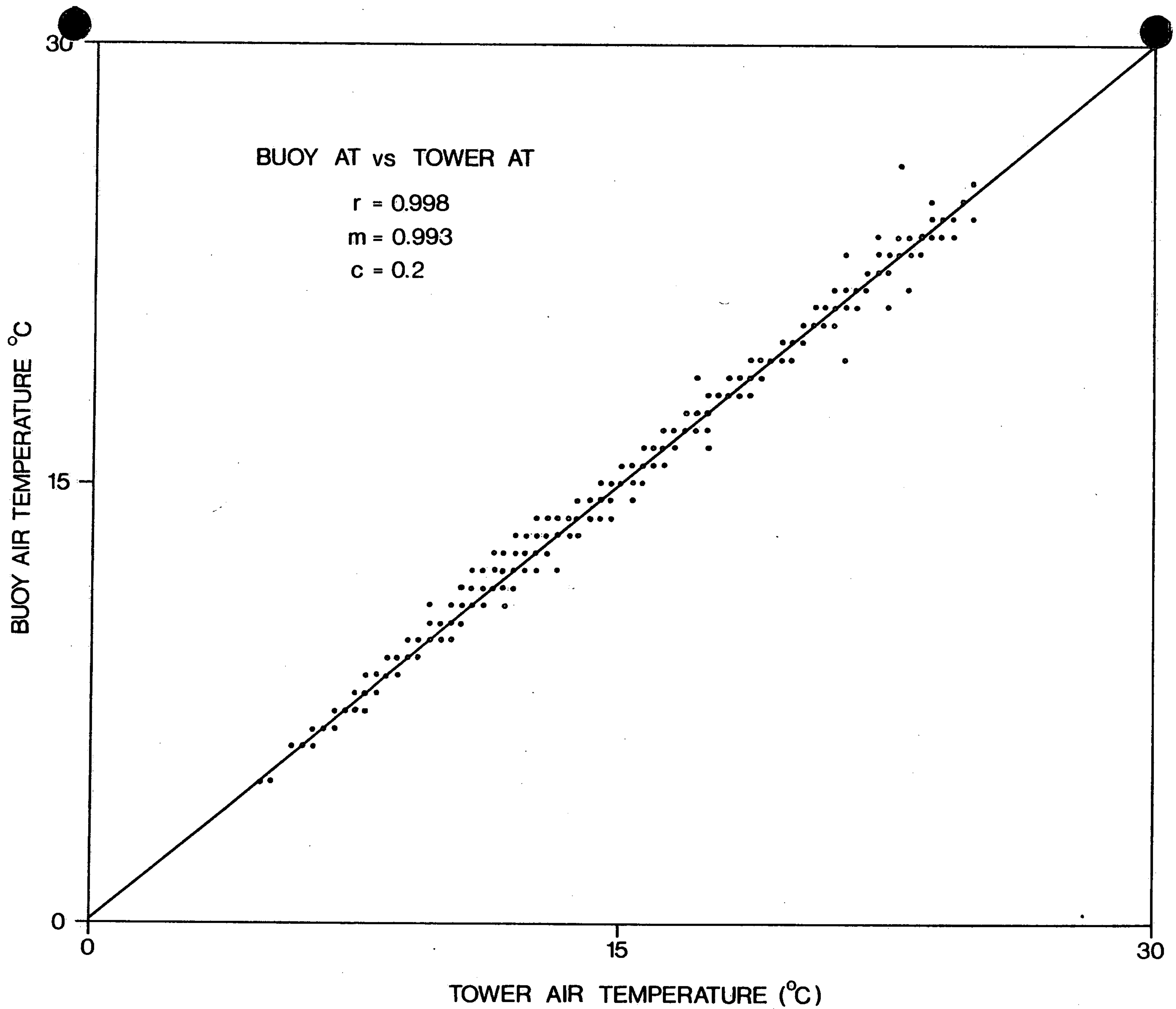

BUOY WS vs TOWER WS
r = 0.992
m = 0.991
c = 16.0
1500
750
0
0
750
1500
BUOY WIND SPEED cm/s
TOWER WIND SPEED (cm / s)

Figure 5



BUOY AT vs TOWER AT
r = 0.998
m = 0.993
c = 0.2
BUOY AIR TEMPERATURE °C
TOWER AIR TEMPERATURE (°C)
0
15
30
0
15
30

Figure 6

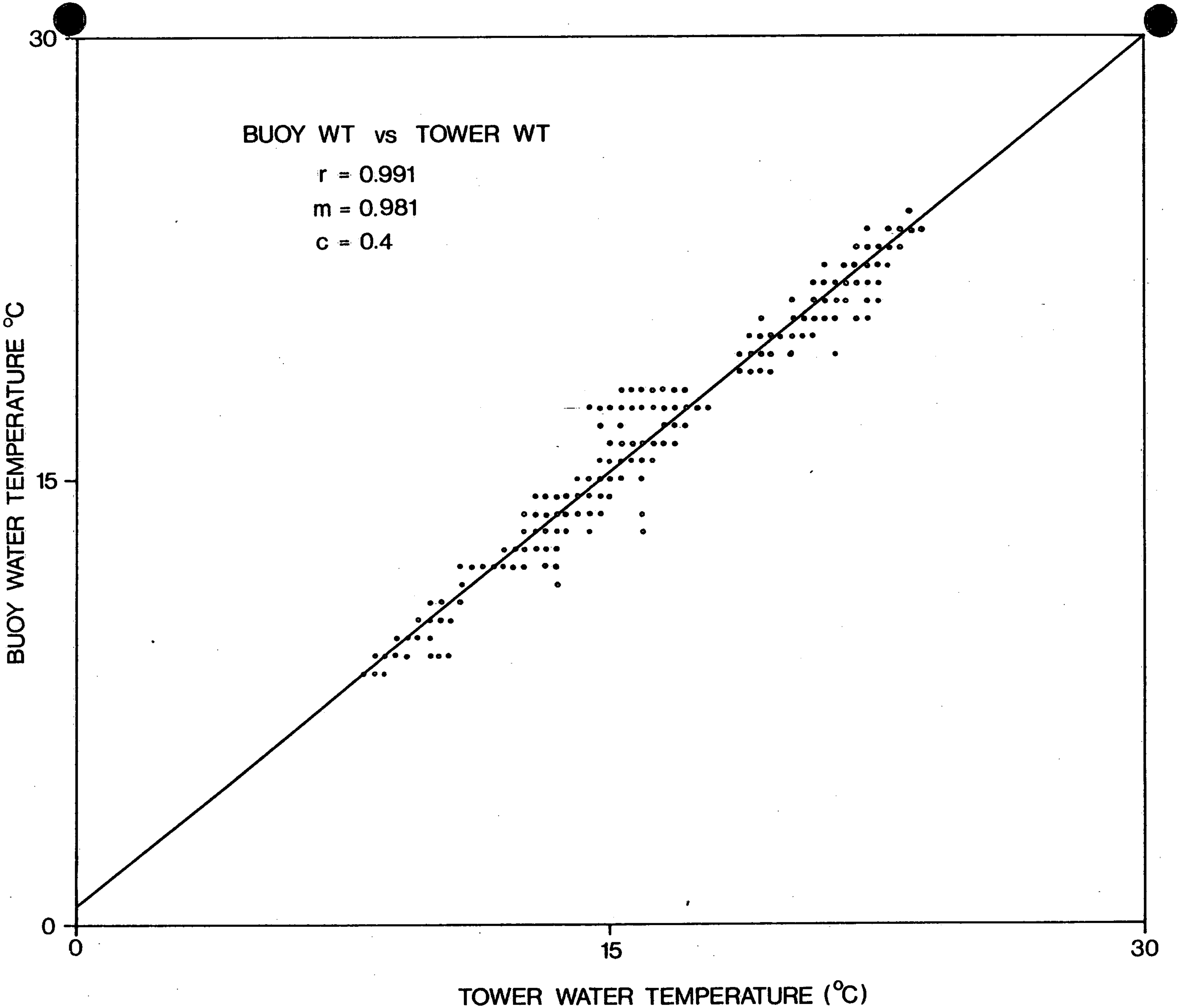

BUOY WT vs TOWER WT
r = 0.991
m = 0.981
c = 0.4
BUOY WATER TEMPERATURE °C
TOWER WATER TEMPERATURE (°C)
30
15
0
0
15
30

Figure 7

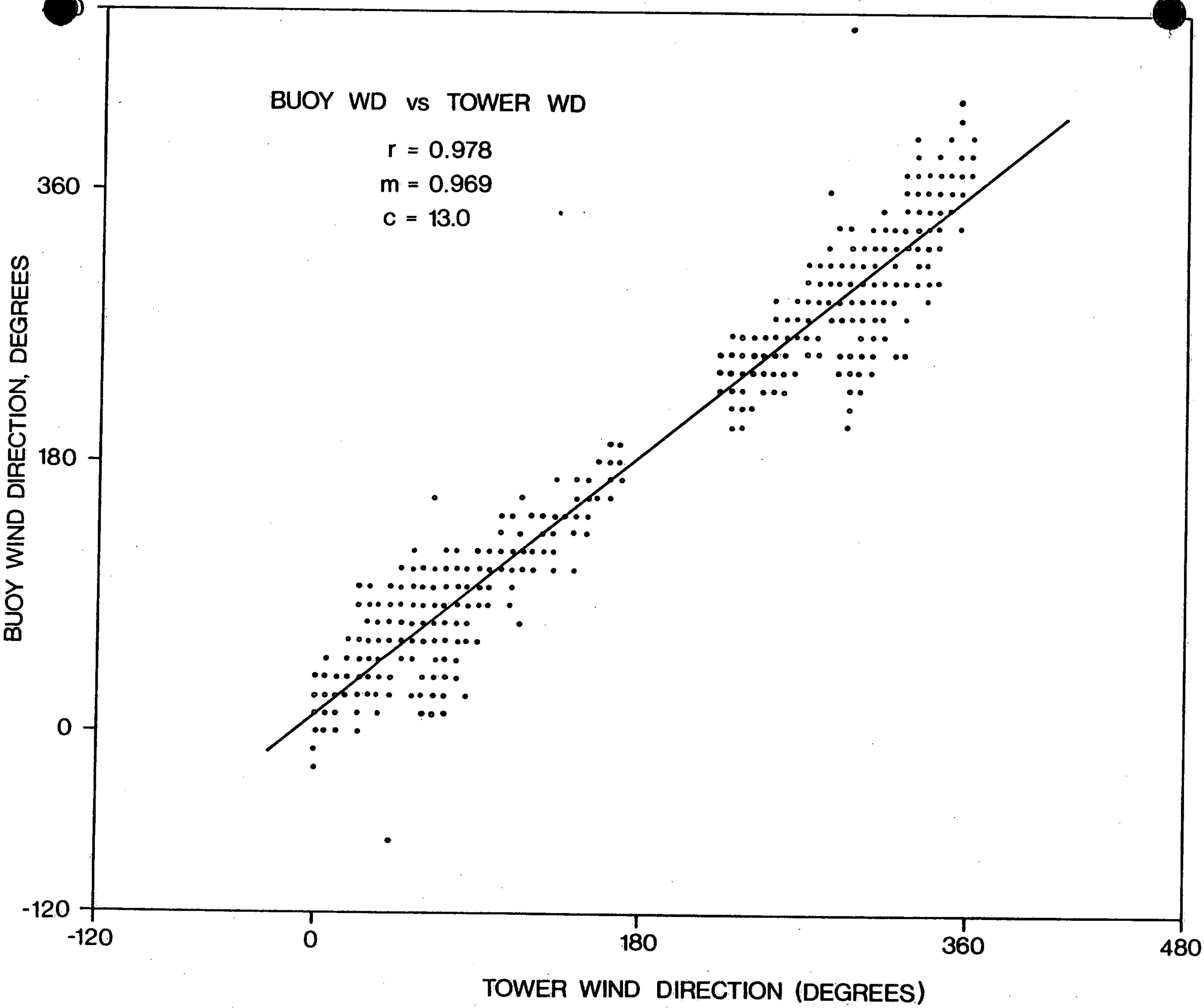
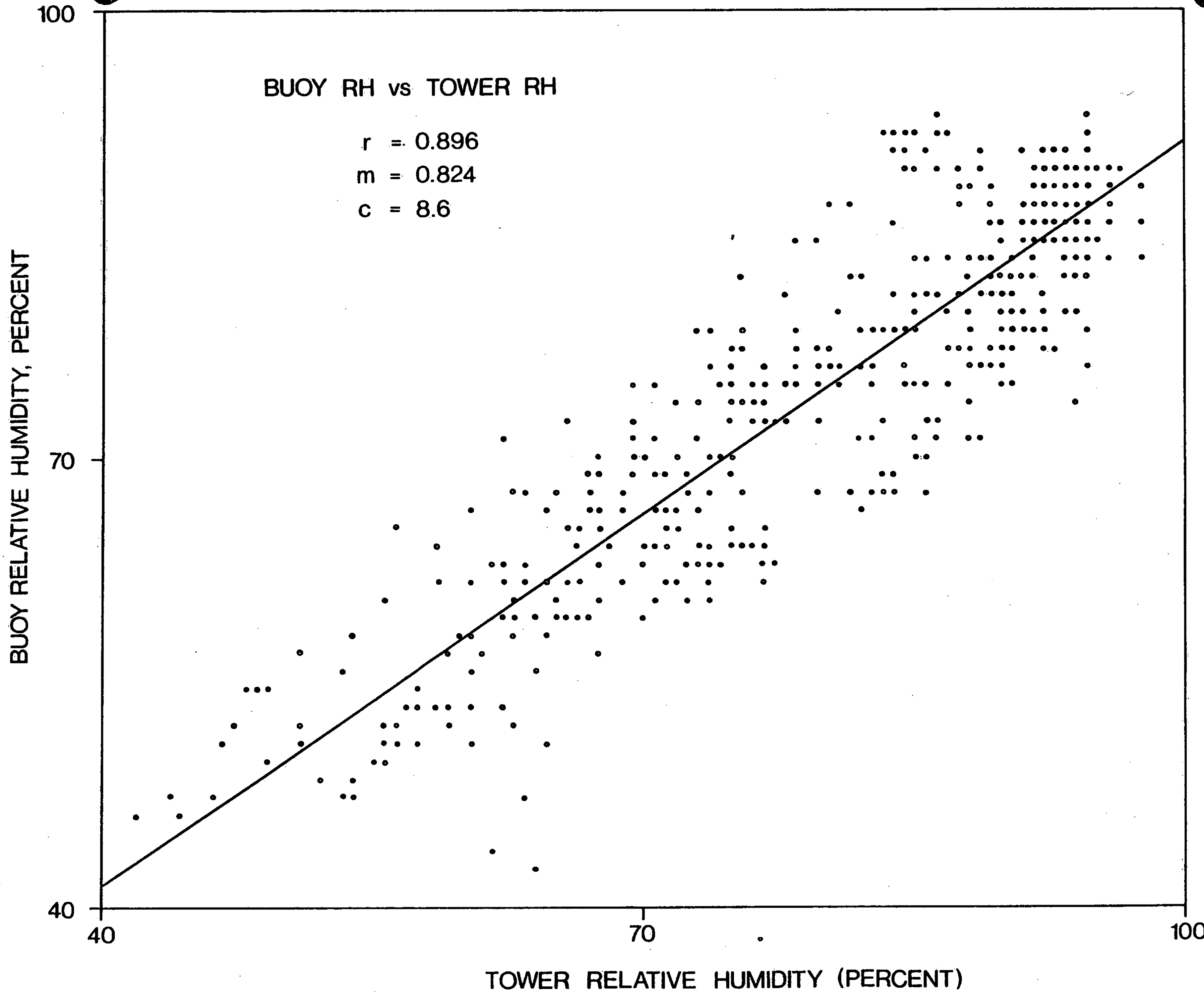

BUOY WD vs TOWER WD
r = 0.978
m = 0.969
c = 13.0
360
180
0
-120
-120
0
180
360
480
BUOY WIND DIRECTION, DEGREES
TOWER WIND DIRECTION (DEGREES)

Figure 8



BUOY RH vs TOWER RH
r = 0.896
m = 0.824
c = 8.6
100
70
40
40
70
100
BUOY RELATIVE HUMIDITY, PERCENT
TOWER RELATIVE HUMIDITY (PERCENT)

Figure 9

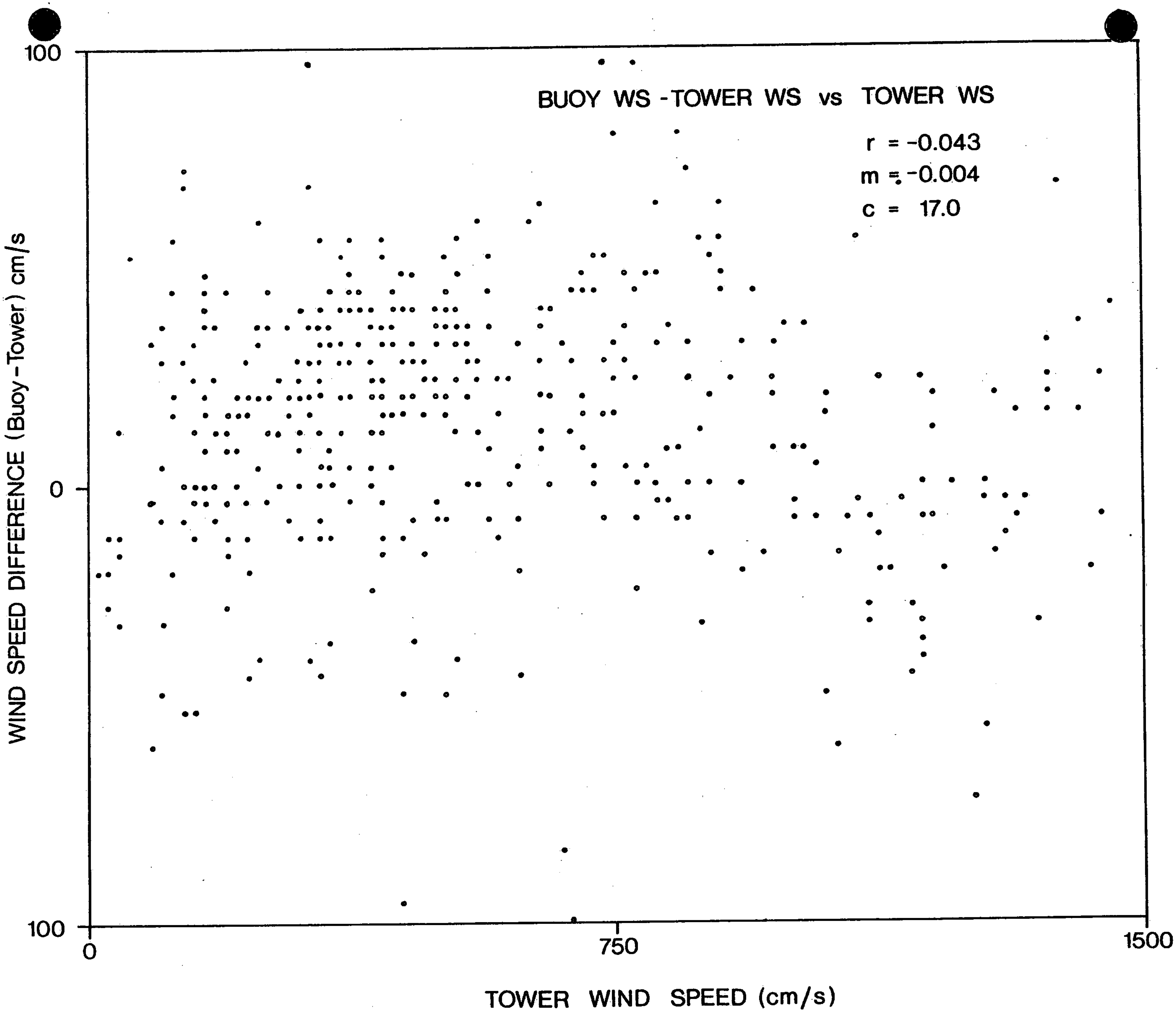
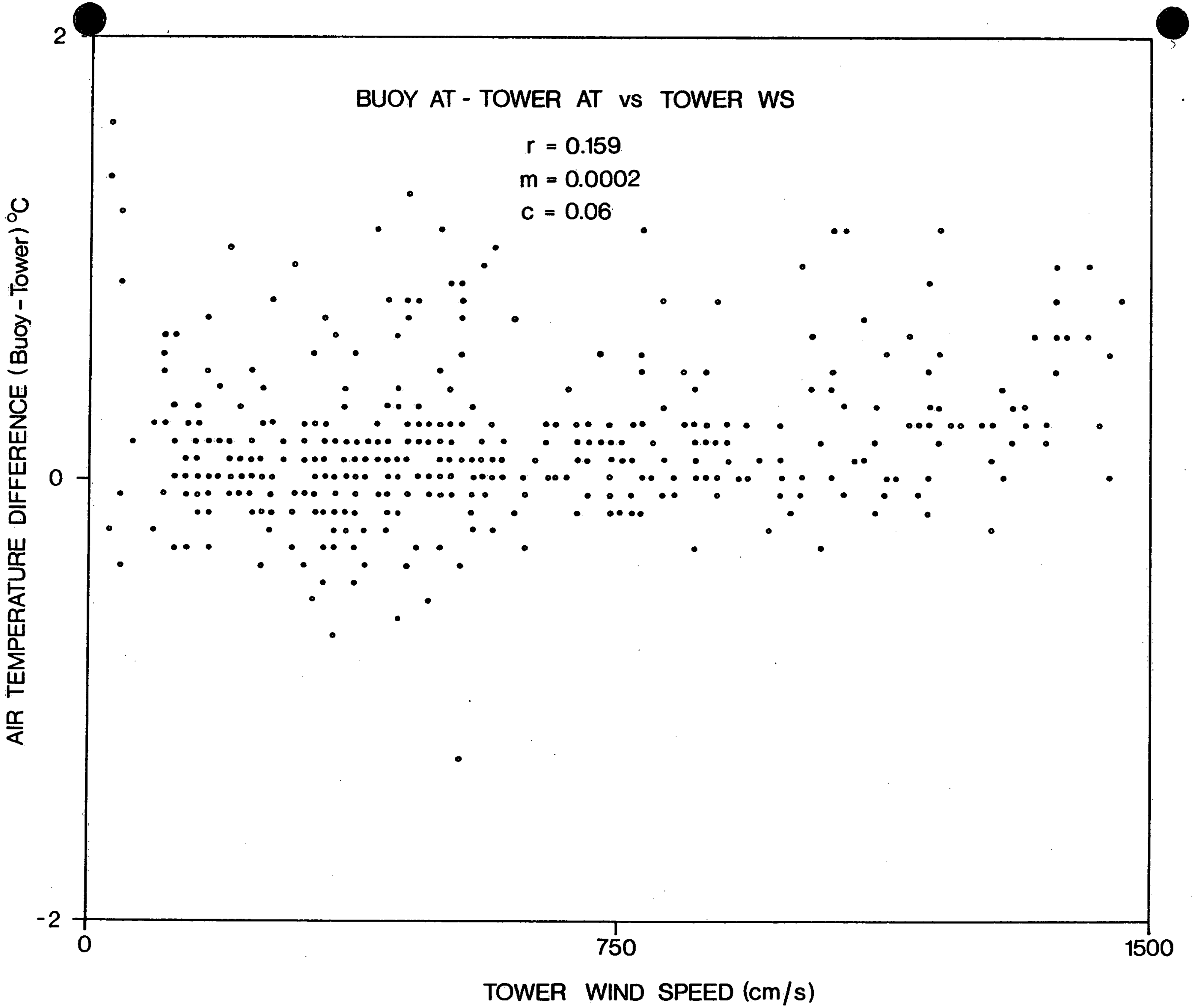

BUOY WS -TOWER WS vs TOWER WS
r = -0.043
m = -0.004
c = 17.0
WIND SPEED DIFFERENCE (Buoy-Tower) cm/s
100
0
100
0
750
1500
TOWER WIND SPEED (cm/s)

Figure 10



BUOY AT - TOWER AT vs TOWER WS
r = 0.159
m = 0.0002
c = 0.06
AIR TEMPERATURE DIFFERENCE (Buoy - Tower) °C
2
0
-2
0
750
1500
TOWER WIND SPEED (cm/s)

Figure 11

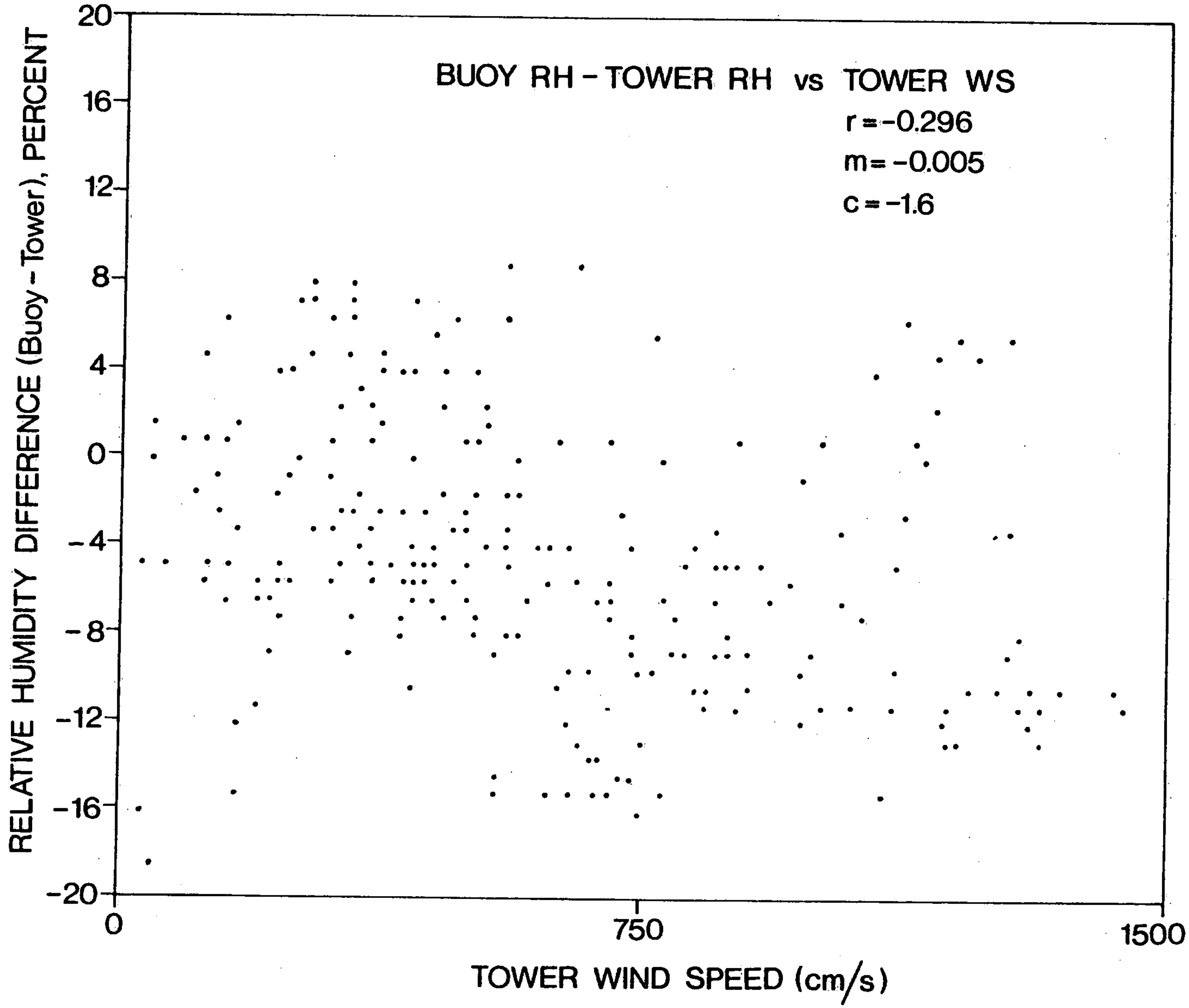

BUOY RH - TOWER RH vs TOWER WS
r = -0.296
m = -0.005
c = -1.6
RELATIVE HUMIDITY DIFFERENCE (Buoy - Tower), PERCENT
20
16
12
8
4
0
-4
-8
-12
-16
-20
0
750
1500
TOWER WIND SPEED (cm/s)

Figure 12

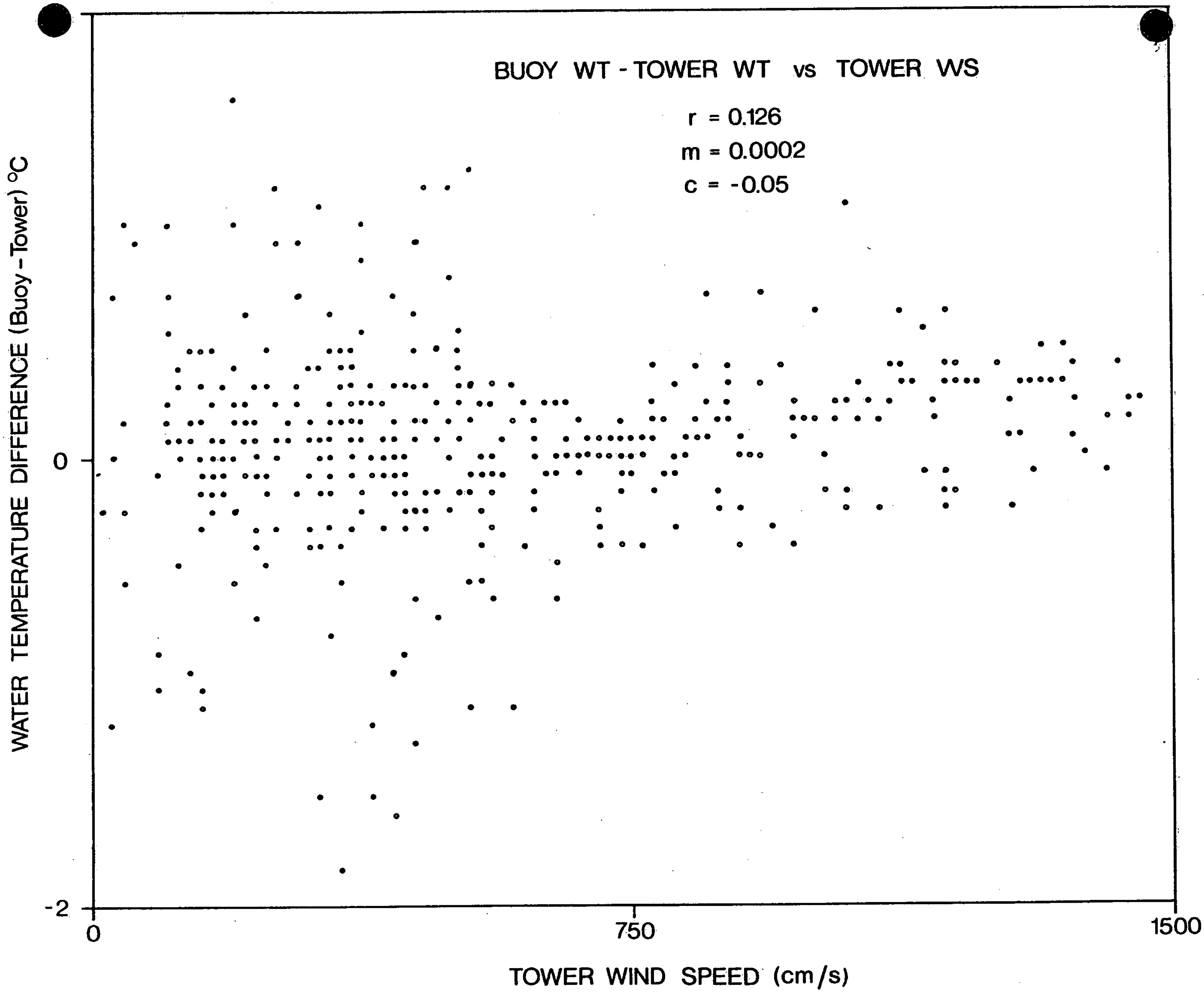

BUOY WT - TOWER WT vs TOWER WS
r = 0.126
m = 0.0002
c = -0.05
WATER TEMPERATURE DIFFERENCE (Buoy - Tower) °C
0
-2
0
750
1500
TOWER WIND SPEED (cm/s)

Figure 13

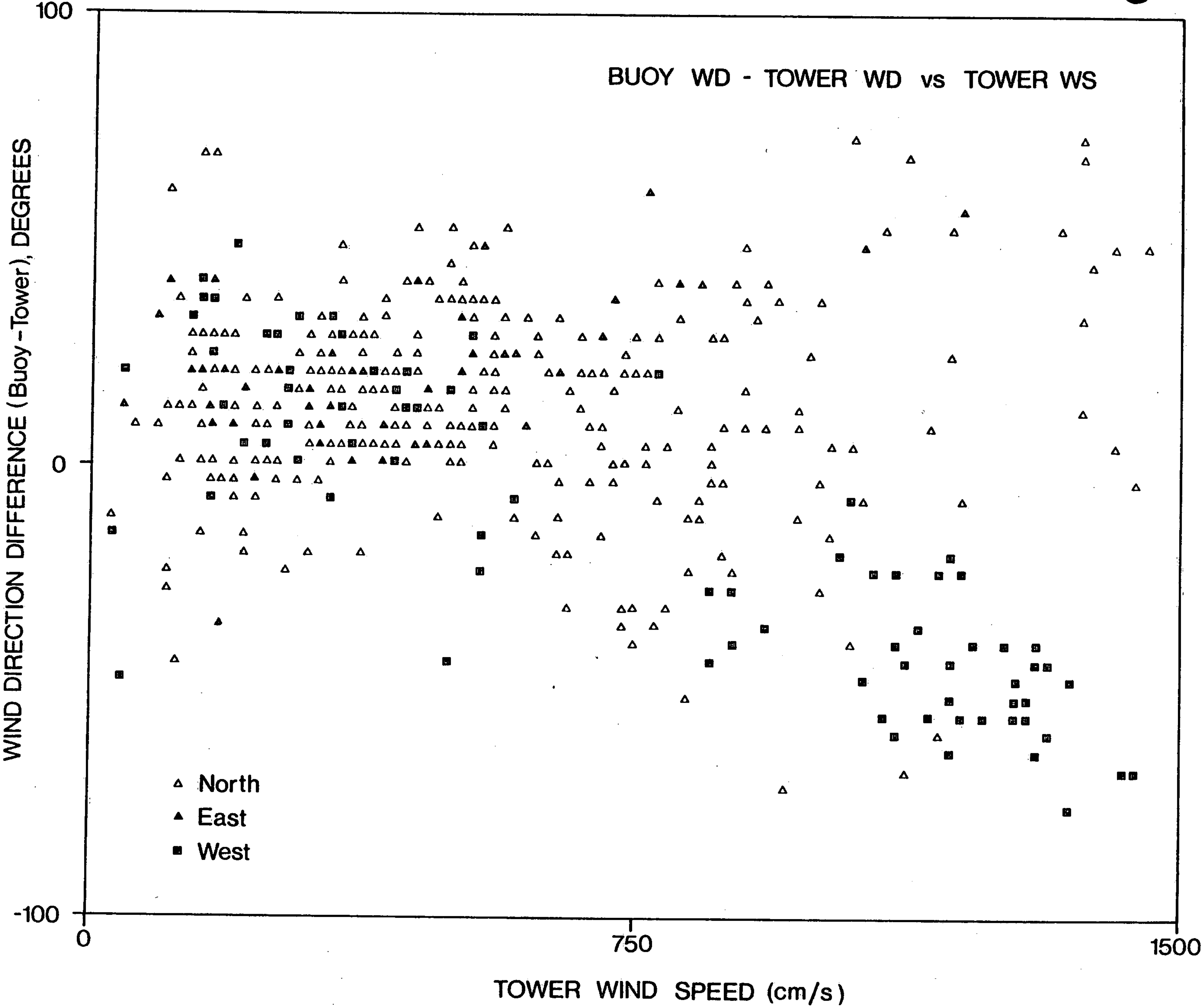

BUOY WD - TOWER WD vs TOWER WS
WIND DIRECTION DIFFERENCE (Buoy-Tower), DEGREES
100
0
-100
0
750
1500
TOWER WIND SPEED (cm/s)
North
East
West

Figure 14

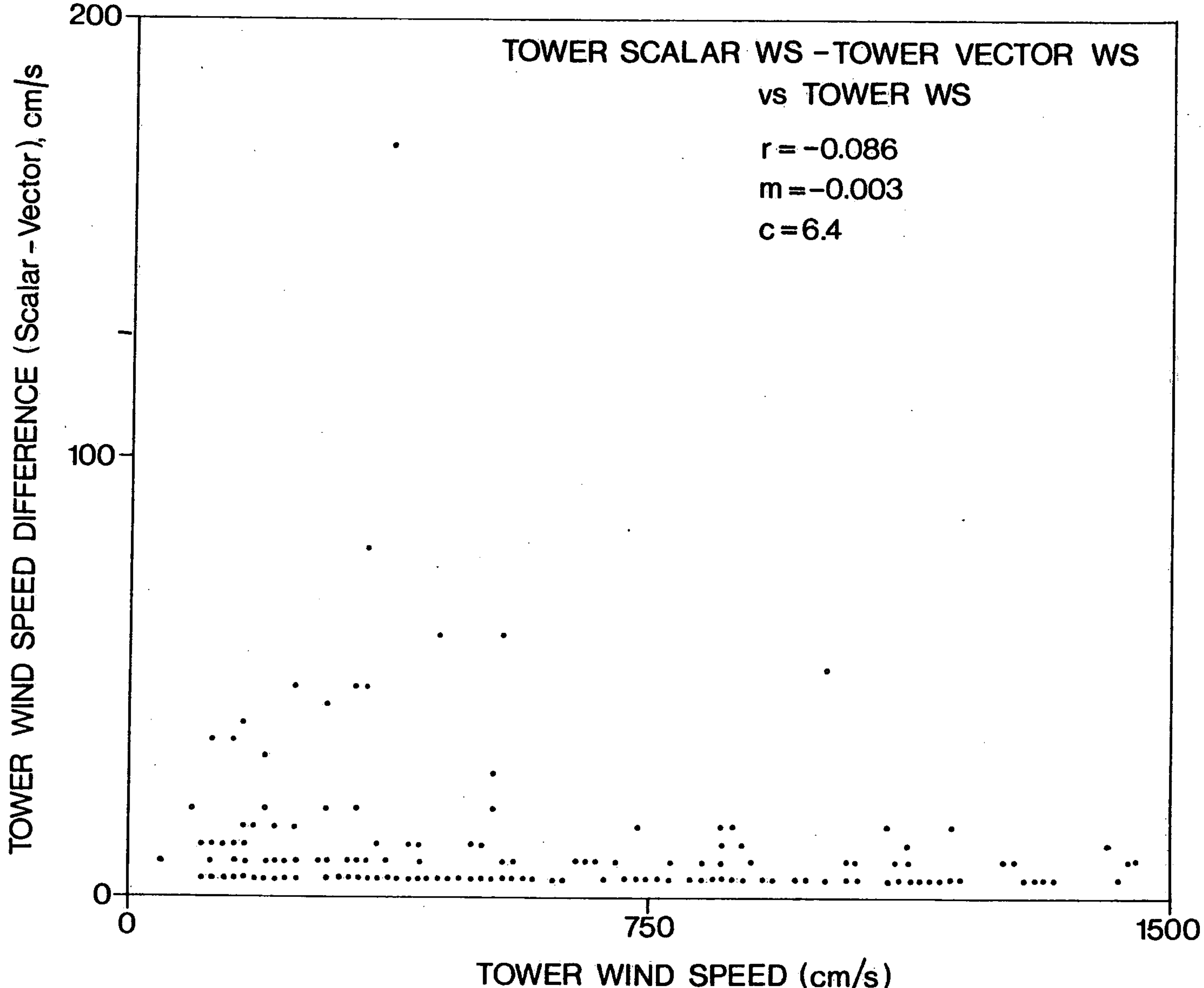
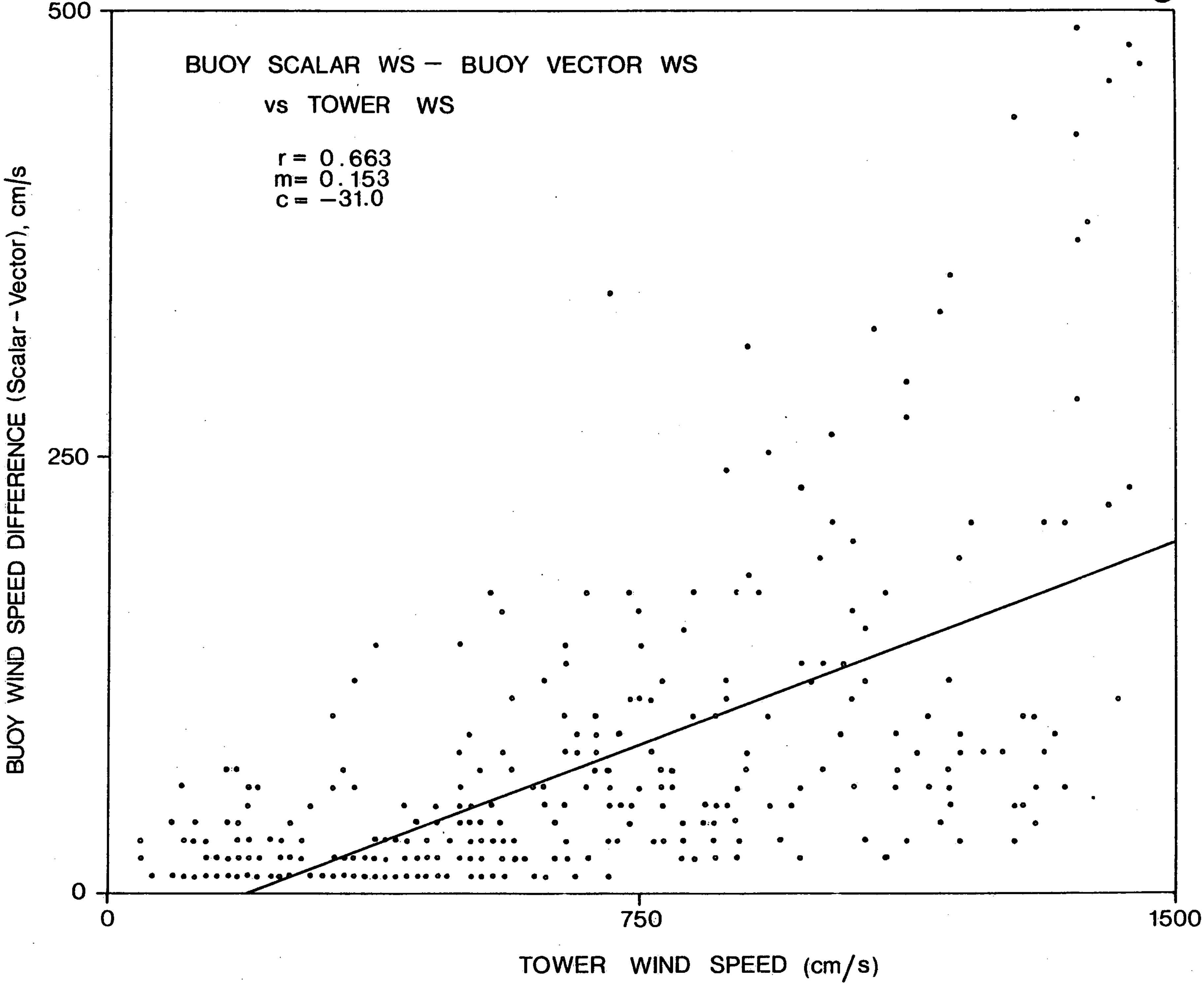

TOWER SCALAR WS - TOWER VECTOR WS
vs TOWER WS
r = -0.086
m = -0.003
c = 6.4
200
100
0
0
750
1500
TOWER WIND SPEED DIFFERENCE (Scalar - Vector), cm/s
TOWER WIND SPEED (cm/s)

Figure 15



BUOY SCALAR WS – BUOY VECTOR WS
vs TOWER WS
r = 0.663
m= 0.153
c = –31.0
500
250
0
0
750
1500
TOWER WIND SPEED (cm/s)
BUOY WIND SPEED DIFFERENCE (Scalar - Vector), cm/s

Figure 16

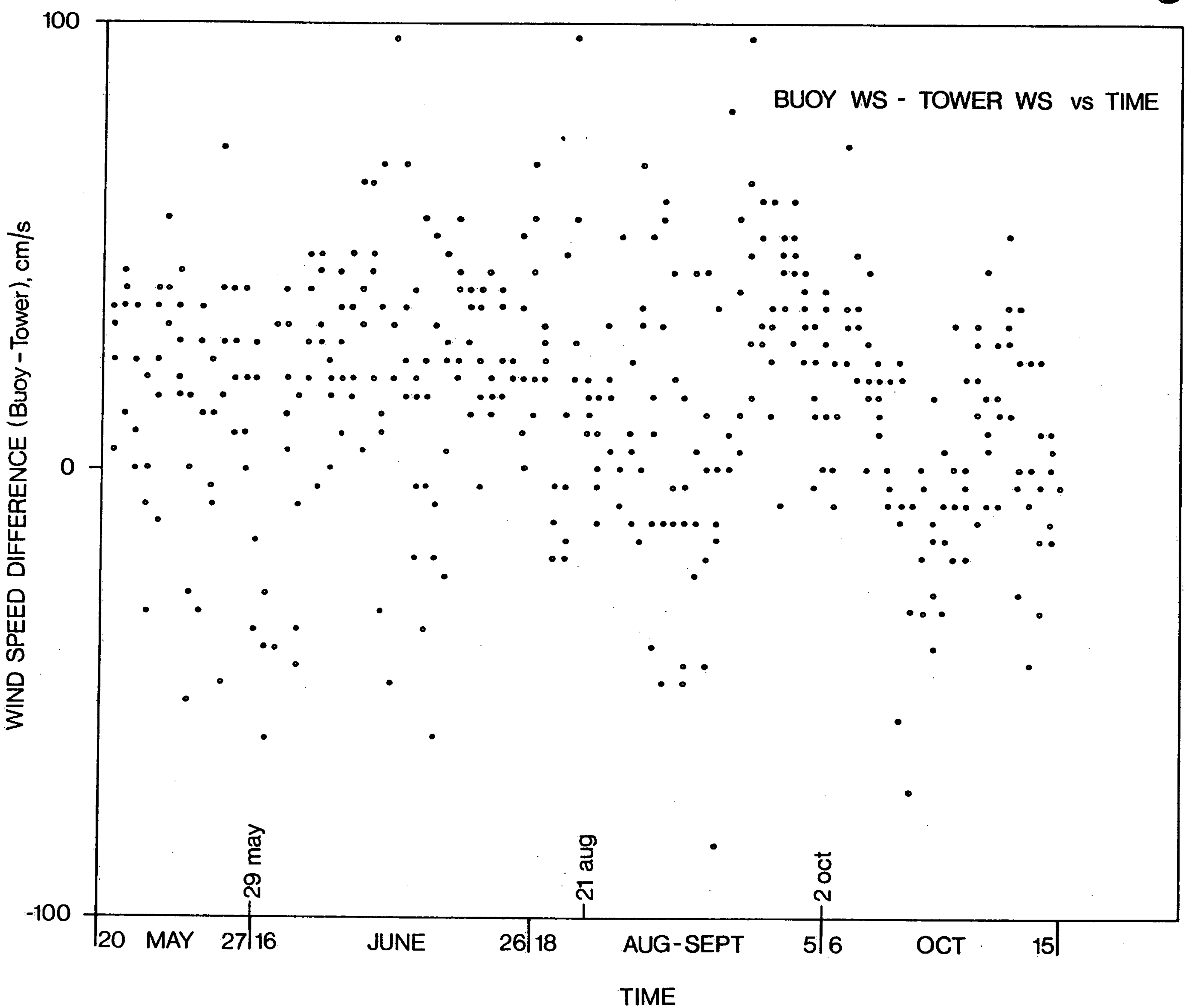

BUOY WS - TOWER WS vs TIME
WIND SPEED DIFFERENCE (Buoy - Tower), cm/s
100
0
-100
29 may
21 aug
2 oct
20
MAY
27
16
JUNE
26
18
AUG-SEPT
5
6
OCT
15
TIME

Figure 17

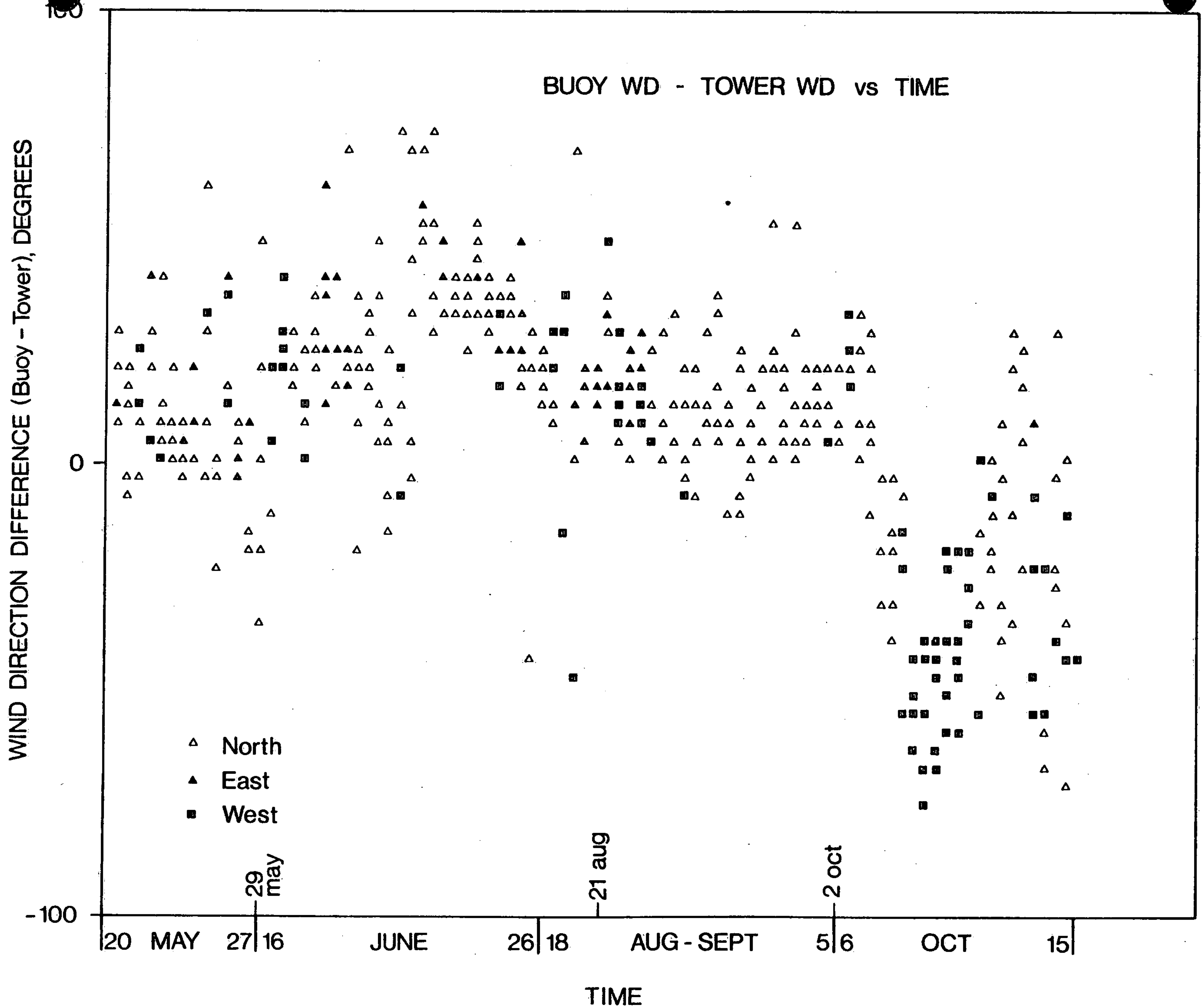

BUOY WD - TOWER WD vs TIME
WIND DIRECTION DIFFERENCE (Buoy - Tower), DEGREES
100
0
-100
North
East
West
29 may
21 aug
2 oct
20 MAY 27 16 JUNE 26 18 AUG - SEPT 5 6 OCT 15
TIME

Figure 18

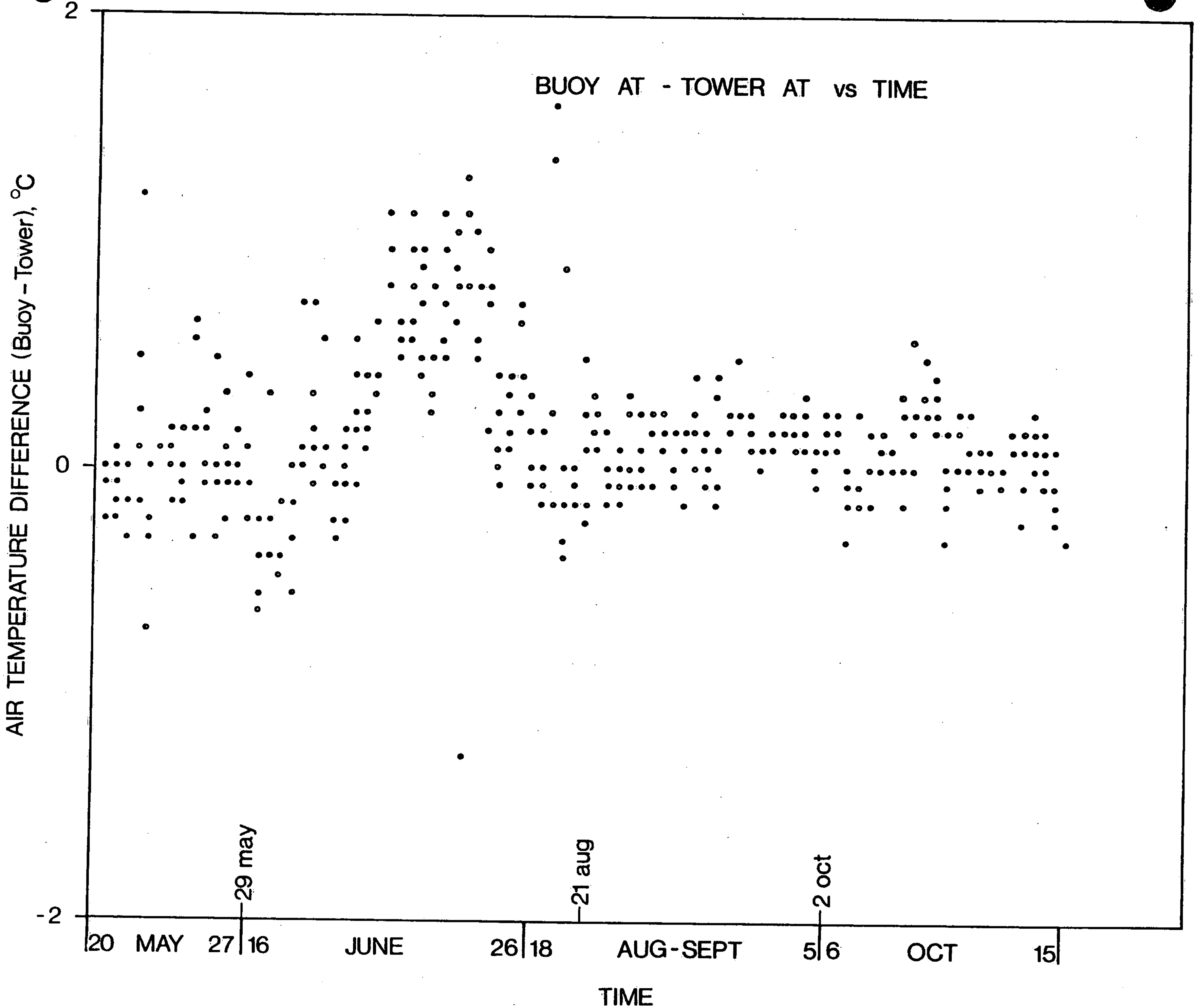

BUOY AT - TOWER AT vs TIME
AIR TEMPERATURE DIFFERENCE (Buoy - Tower), °C
2
0
-2
29 may
21 aug
2 oct
20 MAY 27
16 JUNE 26
18 AUG-SEPT 5
6 OCT 15
TIME

Figure 19

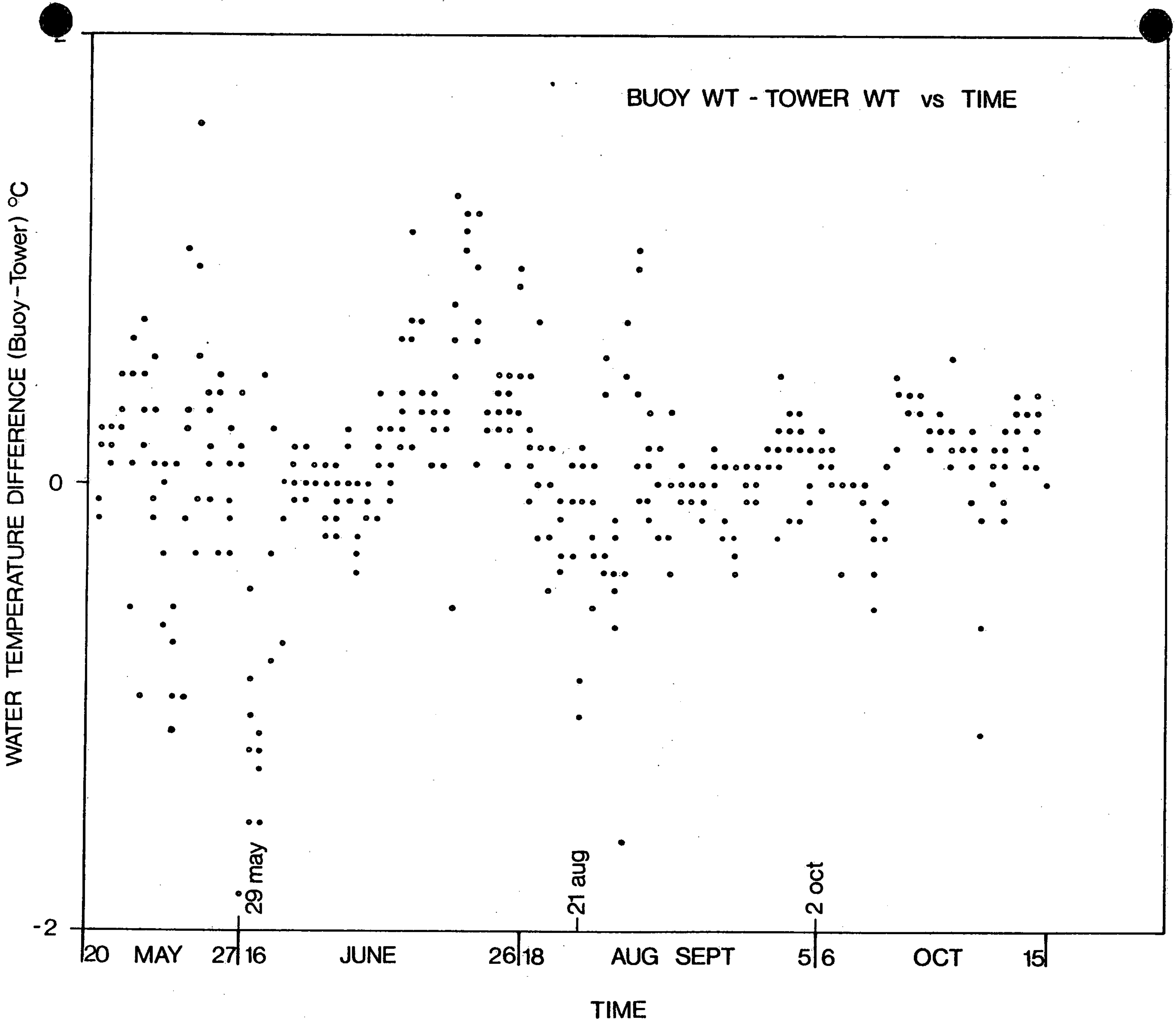
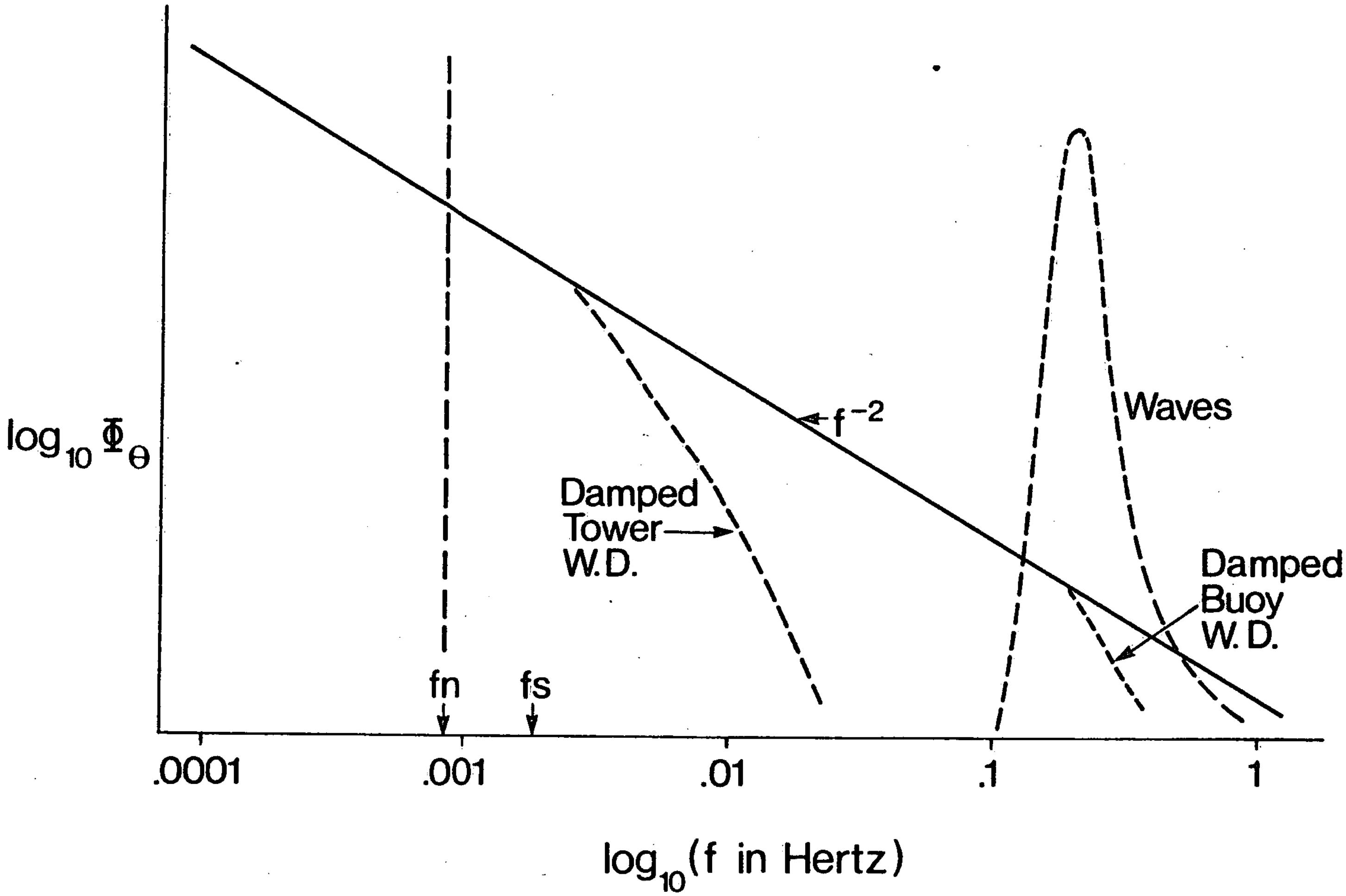

BUOY WT - TOWER WT vs TIME
WATER TEMPERATURE DIFFERENCE (Buoy-Tower) °C
0
-2
29 may
21 aug
2 oct
20
MAY
27
16
JUNE
26
18
AUG
SEPT
5
6
OCT
15
TIME

Figure 20



log10 Φθ
fn
fs
Damped
Tower
W.D.
f−2
Waves
Damped
Buoy
W.D.
.0001
.001
.01
.1
1
log10(f in Hertz)

Figure 21

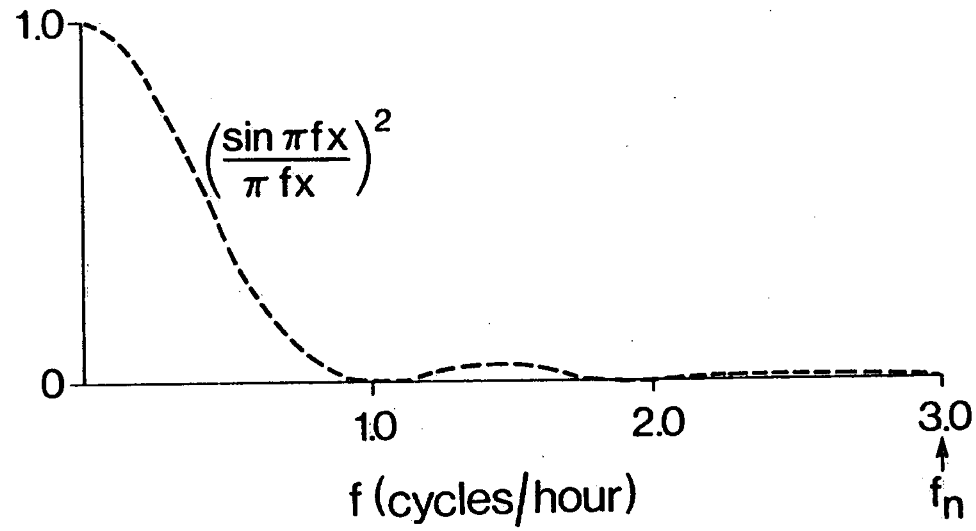


Figure 22