I.O.S.

INSTITUTE OF OCEANOGRAPHIC SCIENCES

WAVES AT OCEAN WEATHER STATION ALPHA

by

D.J.T. Carter

and

L. Draper

Report No. 69

1979

The preparation of this report was supported financially by the Departments of Industry and Energy

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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ABSTRACT

Measurements of surface waves were made intermittently from 1959 to 1971 at Ocean Weather Station Alpha (62°N, 33°W) using Shipborne Wave Recorders. These measurements, scattered throughout the years, have been put together to provide a simulated set of one year's data, which has been analysed to provide an estimate of wave conditions throughout the year. Results are presented in a series of figures, including distributions of wave height and period throughout the year and for individual seasons. Estimates of fifty-year return wave heights are derived. The distribution of zero-up-crossing wave heights is shown to be very close to negative exponential.

CONTENTS

FIGURES

INTRODUCTION

Measurements of surface waves were made intermittently from 1959 to 1971 at Ocean Weather Station Alpha (62°00'N, 33°00'W), where the water depth is greater than 2000 metres. Records for every month of the year, and at some time on 281 days of the year, were obtained during this period; these records have been put together to provide an almost complete set of one year's data. Gaps in this set were filled by various methods, determined partly by the size of the gap. This completed data set was analysed to provide an estimate of wave conditions throughout the year.

WAVE RECORDS AND THEIR ANALYSIS

Wave records were produced from Shipborne Wave Recorders - described by Tucker (1956) - which were fitted in the U.K. Ocean Weather Ships Weather Adviser and Weather Reporter. Analogue traces of surface elevation lasting about 15 minutes were obtained at three-hourly intervals whenever the ship's speed was less than two knots (noticeable errors in estimates of wave period can occur at higher speeds). Going through the days of the calendar year one by one, it was usually possible to find a record at each synoptic hour (0001, 0300, 0600..etc) from at least one year in the period 1959-1971 which had been taken when the Ocean Weather Ship was within about 10nm of 62°N33°W. There are two gaps of 15 days in the records (2-16 July and 16-30 September) and some other shorter gaps. The two gaps of 15 days were filled with data from the preceding and following 7½ days records. Other gaps in the data were filled using data from a different year within two weeks of the date of the missing record; if there was no such record then an adjacent record was duplicated or data were interpolated from the preceding and following record. Approximately 30% of the year was filled with data from within two weeks of the specified dates, and approximately 13% of the year was completed with duplicated or interpolated data.

The amount of data from each month of each year is indicated in Table 1. This shows that most records were from 1967, 1969 and 1971; they are not uniformly distributed throughout the months, for example records for October are all from 1961 or 1963.

The Shipborne Wave Recorder was calibrated to give wave height in feet. This unit was used for the analysis of individual wave recorder traces, and has been employed throughout this report.

The method of analysing the analogue records is based upon a method developed by Tucker (1961) from theoretical studies of Cartwright and Longuet-Higgins (1956); it is fully described by Tann (1976).

Values for the following parameters were taken from each record:

H_1 = The sum of the distances from the mean water level of the highest crest and the lowest trough.

H_2 = The sum of the distances from the mean water level of the second highest crest and second lowest trough.

T_z = The mean zero-up-crossing period, obtained by dividing the duration of the record (in seconds) by the number of occasions the trace passes through the mean water level in an upward direction.

T_c = The mean crest period.

Values of H_1 and H_2 were corrected for the depth below the surface of the pressure sensors, using the formula, involving T_z, given by Darbyshire (1961), (Her equation 1 with $k = 2.5$). Depths of the pressure sensors were assumed constant; 6.3 ft for Weather Adviser and 7.1 ft for Weather Reporter. These are the mean depths for each vessel. On each voyage the depths were greater on departure and less on return.

From these corrected values of H_1 and H_2, together with T_z and T_c, the following were estimated:

H_s = The significant wave height (Defined as 4σ where σ is the root mean square surface elevation).

$H_{max(3\ hours)}$ = The most probable height of the highest zero-up-crossing wave during a three hour period.

ϵ = A spectral width parameter given by $\epsilon^2 = 1 - (T_c/T_z)^2$.

RESULTS

a. Maximum measured wave height.

The highest values of H_1 (corrected) measured at O.W.S. Alpha was 60.2 ft, with T_z of 12.7 seconds, obtained on 29 October 1961. The previous record gave 59.0 ft and 13.3 seconds.

Values of significant wave height and most probable maximum wave height in 3 hours are normally derived statistically from the two measurements H_1 and H_2 taken from a short analogue record. In general, sampling errors would be expected to balance out throughout the year, but for these few very high waves it seemed prudent to determine H_s and $H_{max(3\ hours)}$ by calculating the root-mean-square wave height of the zero-up-crossing waves from the two records. The results (with the values derived from H_1 and H_2 given in brackets) are as follows:

Time on 29 October 1961	H_s (ft)	$H_{max(3\ hours)}$ (ft)
1500	34.0(40.1)	62.3(73.9)
1800	37.1(40.0)	68.5(73.9)

These root-mean-square estimates have been used in this report. The record at 1500 on 29 October appears to be satisfactory with no evidence of instrument malfunction; the large difference between the two estimates of H_s results from one high crest with an unexpectedly deep trough to either side.

The next highest values of H_s and $H_{max(3\ hours)}$ were 33.2 ft and 62.4 ft respectively on 21 January 1965 - with H_1 (corrected) of 49.0 ft and T_z of 10.0 seconds.

b. Lowest measured wave height.

No calm was recorded during the year; on only four occasions was the estimated significant wave height less than 2 ft (all during April/May 1966) with a smallest value of 1.2 ft.

c. Seasonal and annual distributions.

The results of the analysis of all the three-hourly records are shown in the figures, prepared using the form of presentation recommended for engineering purposes by Draper (1967). Some of these figures give results for individual seasons defined as follows:-

Winter: January-March
Spring: April-June
Summer: July-September
Autumn: October-December

Figures 1-4 show the cumulative distribution of H_s and of $H_{max(3\ hours)}$ for each of the four seasons, while Fig. 5 gives the distribution for the whole year. For example, Fig. 1 shows that during the winter the significant wave height exceeded 11 ft for 50% of the time, while Fig. 5 shows that 9 ft was exceeded for 50% of the year.

Figures 6-10 are histograms of the distribution of T_z for each season, and for the year. A comparison of the four seasonal histograms shows that the modal value T_z was least during the summer, at 7-7½ seconds, and greatest during the autumn, at 9-9½ seconds. The largest zero-up-crossing periods observed were 13-13½ seconds during the autumn. The histograms show the smallest values of T_z to be 4½-5 seconds; the rapid attenuation of short waves with depth cause the Shipborne Wave Recorder pressure sensors to be insensitive at shorter periods.

Figure 11 gives the distribution of the spectral width parameter for the whole year. This parameter is particularly affected by the recorder's high frequency cut-off; so figure 11 should only be used for comparison with similar diagrams from other Shipborne Wave Recorder records.

Figure 12 is a scatter diagram showing the joint distribution throughout the year of significant wave height and zero-up-crossing period. For example, most frequent were waves with height 6-8 ft and period 8-8½ seconds, observed for 3.9% of the year, or - since there are 2920 three-hour periods during the year - on about 114 occasions. The asterisk(*) in the figure represents 1 occasion (0.3 parts per thousand) and the plus (+) represents 2 occasions.

Wave steepness is defined as the ratio of wave height: wave length. Lines of constant steepness of 1.20 and 1.40 are drawn in fig. 12. (Wave length L was computed using simple wave theory, i.e. $L = gT^2/2\pi$ where T is the wave period = T_z.)

d. Fifty-year return values of $H_{max(3\ hour)}$ and H_s.

Figures 13 and 14 give the cumulative distribution of $H_{max(3\ hours)}$ for the whole year plotted on log-normal paper and on Weibull distribution paper respectively, at intervals of 2 feet.

Figures 15 and 16 give similar plots of H_s. (There is no theoretical justification for either distribution, but they have been used satisfactorily elsewhere.)

The Weibull distribution for wave height h is given by the cumulative probability distribution

$$P(H<h) = \begin{cases} 0 & h<A \\ 1 - \exp\left[-\left(\frac{h-A}{B}\right)^C\right] & h \geq A \end{cases} \qquad \text{(Eq.1)}$$

where B, C > 0.

From which:

$$\ln(h-A) = \ln B + \frac{1}{C}\ln(-\ln(1-P)) \qquad \text{(Eq.2)}$$

The data were plotted in figs. 14 and 16 assuming a two-parameter Weibull distribution, i.e. A = 0.

The data points on the log-normal paper appear to lie close to a smooth curve; and on the Weibull paper, for wave heights greater than about 15 feet ($H_{max(3\ hour)}$) and 10 ft (H_s), they approximate to a straight line. A curve and a straight line have been added to figs. 13 and 14 respectively, and have been extrapolated to give 50-year return values of $H_{max(3\ hours)}$ of 78 ft (log-normal) and 85 ft (Weibull). The straight line in fig. 14 was fitted by least-squares regression of wave height on probability to the points plotted above 15 ft which gave B = 20.49 and C = 1.737.

Fitting a line to points above 15 ft, using a three-parameter Weibull with A = 1.0 ft gave a slightly higher estimated for the 50-year return value of 86 ft.

The curve in fig. 13 was drawn by eye, and an unsatisfactory amount of extrapolation was required to obtain the 50-year return value. Thus the best estimate that can be made for the 50-year return value of $H_{max(3\ hours)}$ at Ocean Weather Station Alpha from the wave records obtained intermittently from 1959 to 1971 is about 85 ft.

Similarly, figures 15 and 16 give estimates of the 50-year return value of H_s of 44 ft (log-normal) and 46 ft (Weibull). Using a three-parameter Weibull with A = 1.0 ft gives a value of 47 ft. So the 50-year return value of H_s during 1959-1971 was probably about 46 ft.

Note that the 50-year return value of H_s or $H_{max(3\ hour)}$ is that value which is reached on average once in 50 years. It is not the most probable maximum value in 50 years nor is it the 50-year return value of individual zero-up-crossing wave heights. The most probable maximum value of $H_{max(3\ hours)}$ in 50 years may be estimated as follows:

Assuming $H_{max(3\ hours)}$ has a Weibull distribution, then the cumulative probability, Q, that N values are less than h is given, from equation 1, by

$$Q(H < h) = \left\{1 - \exp\left[-\left(\frac{h-A}{B}\right)^C\right]\right\}^N \qquad \text{(Eq. 3)}$$

and the modal value of h is given by

$$\frac{d^2Q}{dh^2} = 0$$

which reduces to

$$\exp\left[-z^C\right] = \frac{Cz^C - C + 1}{NCz^C - C + 1} \qquad \text{(Eq. 4)}$$

where

$$z = \frac{h-A}{B}$$

Solving equation 4 numerically with A = 0 and the previously derived values of B = 20.49 and C = 1.737, and with N = 50 x 2920 gives the value of h, the most likely highest value of $H_{max(3\ hour)}$ in fifty years, as 85.4 ft.

In general it may be shown from equation 3 - using the technique given by Longuet-Higgins (1952) (p.260) for the Rayleigh distribution - that for large N

$$\text{Mode}\left(H_{max(3\ hour)} \mid n\ \text{year}\right)$$
$$= n\text{-year return value} \cdot \left\{1 + O\left(\ln N\right)^{-\frac{C+2}{C}}\right\} \qquad \text{(Eq. 5)}$$

where N is the number of 3-hourly values in n-years.

e. Distribution of zero-up-crossing wave heights.

The distribution of zero-up-crossing wave heights and their 50-year return value may be estimated following the technique described by Battjes (1970). For each 3 - hourly period, given significant wave height and zero-up-crossing period and assuming wave heights have a Rayleigh distribution, an estimate is obtained of the number of waves greater than 4 ft, 8 ft, ... etc, up to about twice the maximum significant wave height during the year. Summation of the results throughout the year gives an estimate of the cumulative distribution of wave heights. (In practice an approximate summation is obtained using the H_s, T_z distribution given by fig. 12). These cumulative values are fitted to a Weibull distribution and the 50-year return value estimated, assuming independence of individual zero-up-crossing wave heights, by linear regression of the values plotted on Weibull paper.

The total number of waves during the year, N_T, at O.W.S. Alpha was estimated to be 3.88×10^6, of which for example 2 were greater than 68 ft. Figure 17 shows the results plotted, assuming a three-parameter Weibull with A = 1.4 ft (determined experimentally as giving the smallest residual mean square). The regression line gives the 50-year return value (with probability $1 - \frac{1}{50N_T}$) of 91.8 ft.

The other parameters of the Weibull distribution were obtained from the linear regression as B = 4.71 and C = 0.998. The standard error of the regression line slope was 0.003, so the value of the slope which is seen from equation 2 to be 1/C, differs insignificantly from 1; indicating that the zero-up-crossing waves come from a negative exponential distribution.

Battjes (1970) found that other wave data implied the wave height distribution to be "nearly exponential". He fitted wave heights from the Ocean Weather Stations in the N.E. Atlantic ('India' and 'Juliett') to a two-parameter Weibull and obtained values for C of 0.97 and 0.99 respectively; and data from five Light Vessels around the U.K. gave him C between 0.93 and 1.06 except for Morecambe Bay light vessel for which he obtained C = 0.85. Fitting the 'Alpha' wave data to a two-parameter Weibull gives C = 0.90 - significantly different from 1.

From equation 2, with C = 1, the negative exponential distribution is given by

$$h = A - B \ln(1 - P) \qquad \text{(Eq. 6)}$$

So a plot of $h : -\ln(1-P)$ should approximate to a straight line. The result is shown in figure 18. Linear regression gives A = 1.65, B = 4.69, and a 50-year return wave height of 91.2 ft.

The negative exponential distribution cannot hold for wave heights less than A, and must become increasingly inaccurate as wave heights decrease towards A - as indicated in the following table:

Percentage of waves with height less than specified value

height (ft)	from data	from neg. exponential distribution
4	42	39
3	30	25
2	16	7

Thus the data appear to fit the distribution quite closely for wave heights greater than about 3 ft.

ANALYSIS OF WIND SPEEDS AT OWS ALPHA

A comparison of wind strength during the time of wave observations with average values is required in order to relate the wave observations to the wave climate. Wind velocities have been measured at OWS Alpha since July 1956 - at three-hourly intervals whenever the ship was on station until 1962, thereafter at hourly intervals. Wind speeds for each month over 18 years up to June 1974 have been analysed to obtain the following for each of these 216 months:

(a) Ratio of mean wind speed each month to that month's average during the 18 years.

(b) Percentage of each month during which wind speed exceeded 40 knots, and the average percentage for each calendar month during the 18 years.

These monthly values were weighted with the number of days of wave measurements from each month of each year given in Table 1, to obtain an estimate of mean wind speed during the times of wave measurements compared with mean conditions during the 18 years of wind data. Similarly, an estimate was obtained of the percentage of time wind speeds exceeded 40 knots during the composite year of wave measurements and compared with the average percentage during the 18 years.

The ratio of mean wind speed during the year of wave measurements to the average speed over the 18 years 1956-1974 was 0.94. The proportion of time wind speeds exceeded 40 knots during the wave measurements is estimated at 2.3%, compared with a mean annual value from 1956-1974 of 2.5%; a rationof 0.92.

These results are not precise comparisons of wind speeds during the time of wave observations with average condtions, because no allowances were made either for variations during individual months of mean speed and frequency of strong winds or for gaps in the wind data when the ship was off station. Nevertheless, they suggest that winds were less severe than normal during the periods of wave measurements, with speeds reduced on average by about 6%, indicating that wave heights during the years 1958-1974 were on average of the order of 6-12% higher than values obtained from the measuremnts analysed in this report.

CONCLUSIONS

Wave measurements from a Shipborne Wave Recorder obtained intermittently over the thirteen years 1959 to 1971 at OWS Alpha have provided a set of data covering about 87% of the year. Gaps have been filled to yield a composite year's data set, which has been analysed to give the results shown in the figures of this report.

An analysis of wind speeds measured at OWS Alpha during 1956-1974 indicates that wind speeds were around 6% higher than those during the composite year of wave measurements; so that wave heights at OWS Alpha during these 29 years were probably on average about 6% - 12% higher than those obtained from the composite data set.

The 50-year return values of $H_{max(3\ hours)}$ and H_s at OWS Alpha were estimated from the data set, assuming a Weibull distribution to be 85 feet (26m) and 46 feet (14m) respectively. Allowing for the relatively low wind speeds and the relative absence of high winds during the years of wave measurements, the 50-year return values during the period 1956-1974 were probably higher, with $H_{max(3\ hours)}$ in the range of 90-95 feet (27-29m) and H_s in the range of 49-52 feet (15-16m). The most probable highest value of $H_{max(3\ hour)}$ in fifty years is higher than the 50-year return value, but only by an insignificant amount of about 0.2 ft ($<$0.1m).

Zero-up-crossing wave heights greater than about 3 ft (1m) appear to fit closely to a negative exponential distribution. Extrapolation from this fit leads to an estimate of the 50-year return value of zero-up-crossing wave height, from the 1959-71 data, of 91 ft (28m); correcting for the lighter winds during these years, gives a return value of 97-102 ft (29-31m).

ACKNOWLEDGEMENTS

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Table 1. Distribution of wave records by month and year: the number of days of records each month (eight per day rounded to the nearest day). Figures are after gap filling - see 'Wave Records and their Analysis'.

Year / Month	1959	1961	1963	1965	1966	1967	1968	1969	1970	1971	Total
Jan				9		20	2				31
Feb								9		19	28
Mar								2	21	8	31
Apr						15				15	30
May					16	1		14			31
June					3			9	18		30
July				11		11			9		31
Aug				15		8		8			31
Sept		3	4					23			30
Oct		12	19								31
Nov		5				14		1		10	30
Dec	3							16		12	31
Total	3	20	23	35	19	69	2	82	48	64	365

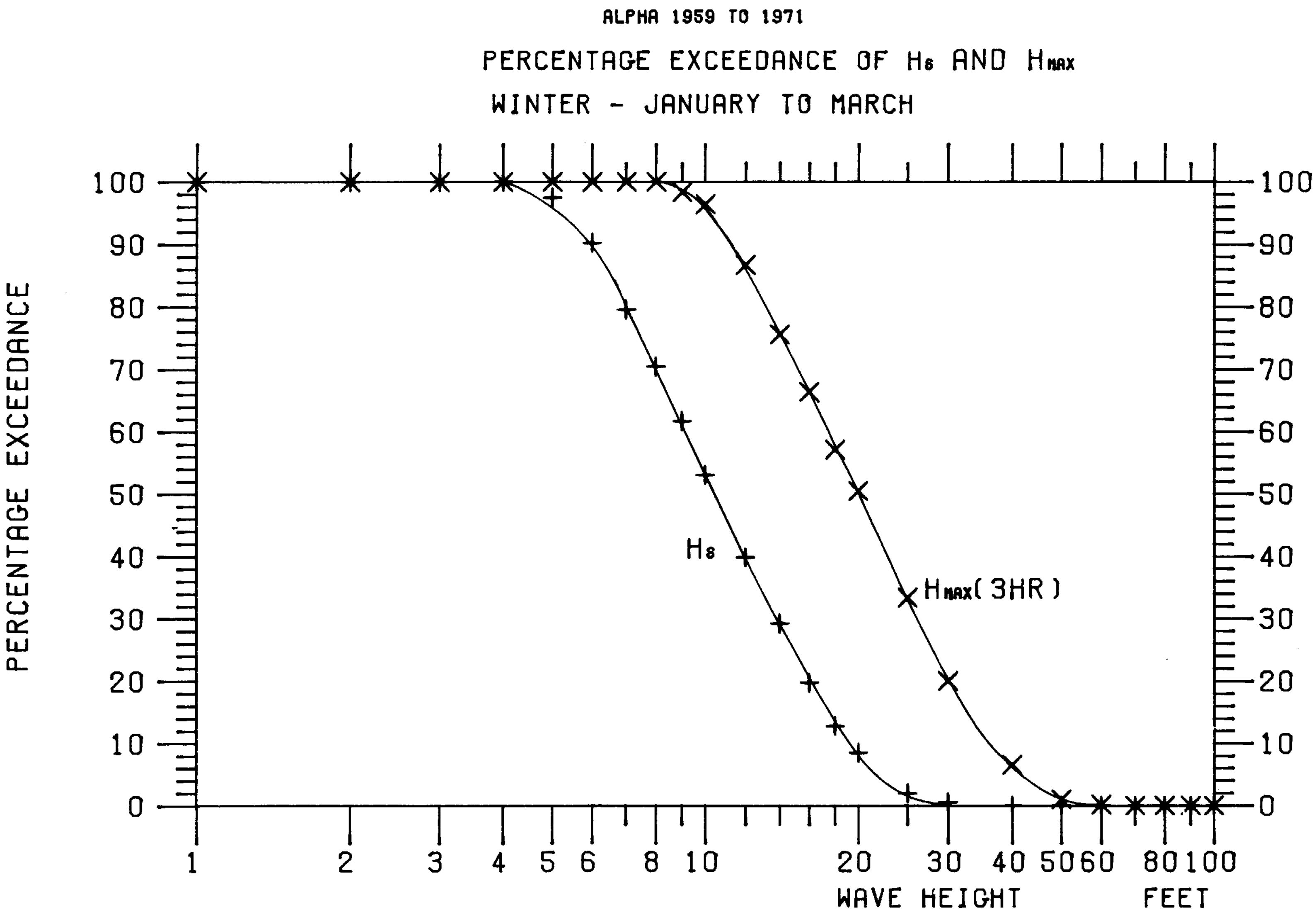
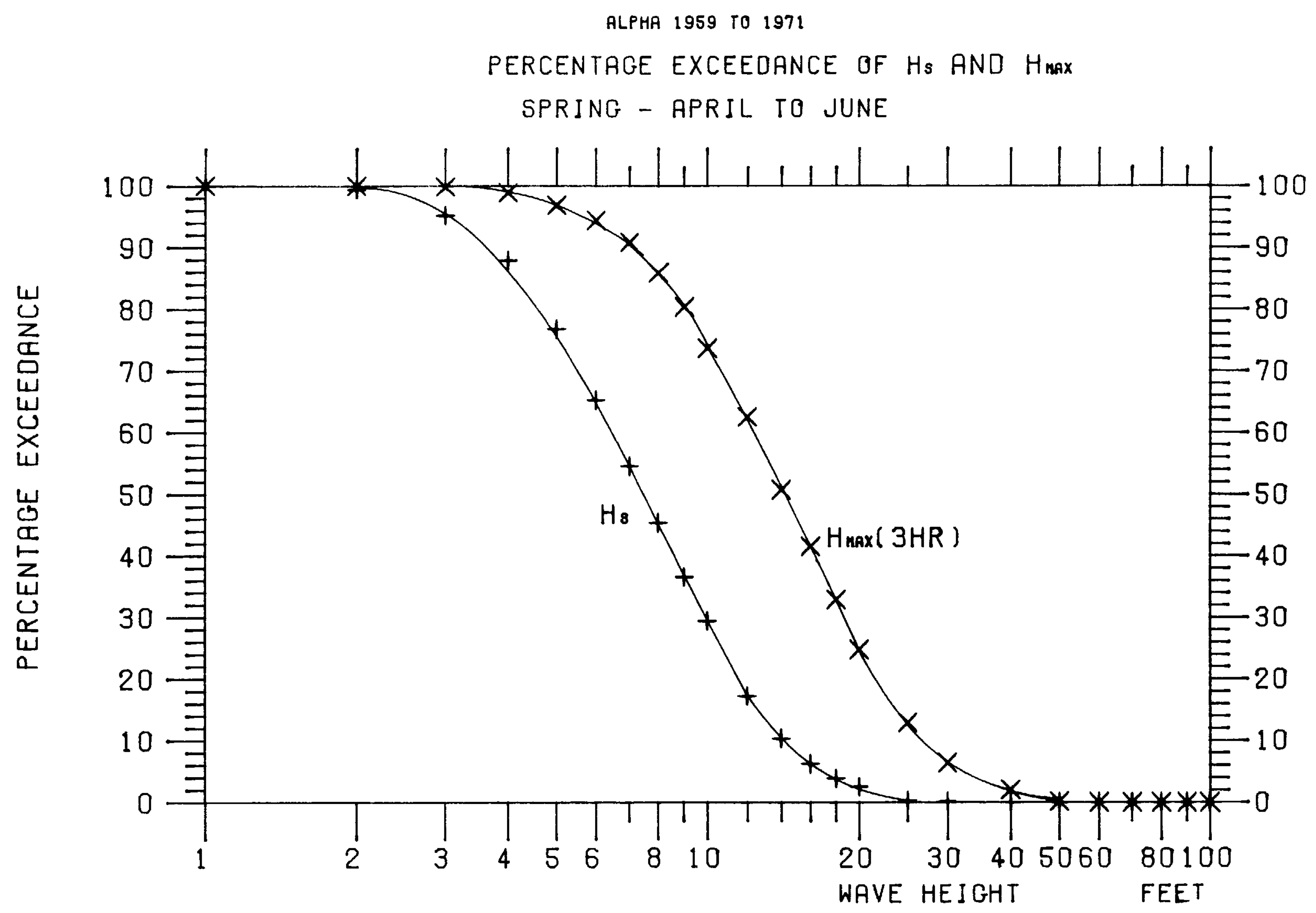

ALPHA 1959 TO 1971
PERCENTAGE EXCEEDANCE OF Hs AND Hmax
WINTER - JANUARY TO MARCH
PERCENTAGE EXCEEDANCE
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
WAVE HEIGHT
FEET
Hs
Hmax(3HR)

FIG.1



ALPHA 1959 TO 1971
PERCENTAGE EXCEEDANCE OF Hs AND HMAX
SPRING - APRIL TO JUNE
PERCENTAGE EXCEEDANCE
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
Hs
HMAX(3HR)
WAVE HEIGHT
FEET

FIG. 2

ALPHA 1959 TO 1971

PERCENTAGE EXCEEDANCE OF H_s AND H_{MAX}

SUMMER - JULY TO SEPTEMBER

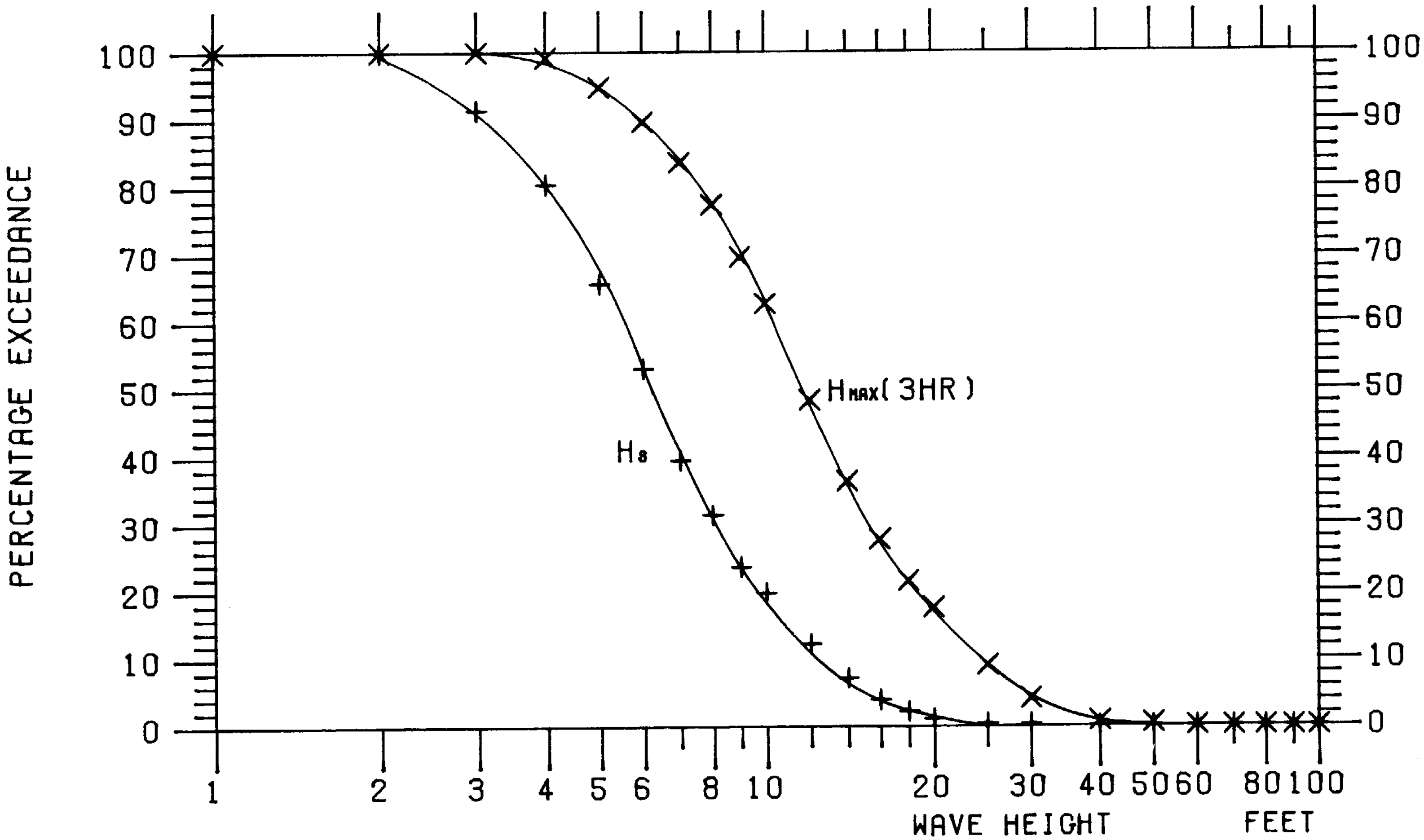


FIG. 3

ALPHA 1959 TO 1971

PERCENTAGE EXCEEDANCE OF H_s AND H_{MAX}

AUTUMN - OCTOBER TO DECEMBER

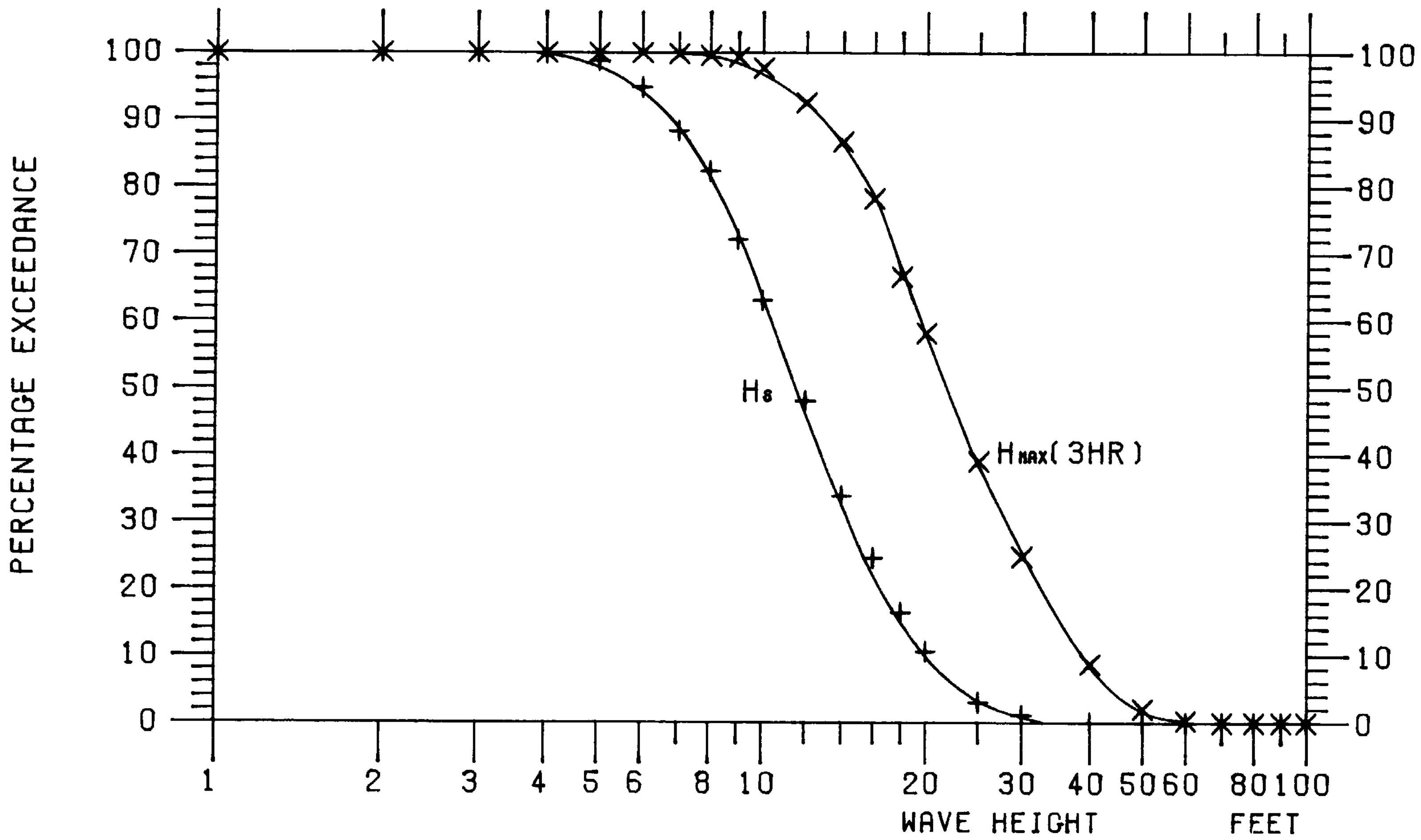


FIG.4

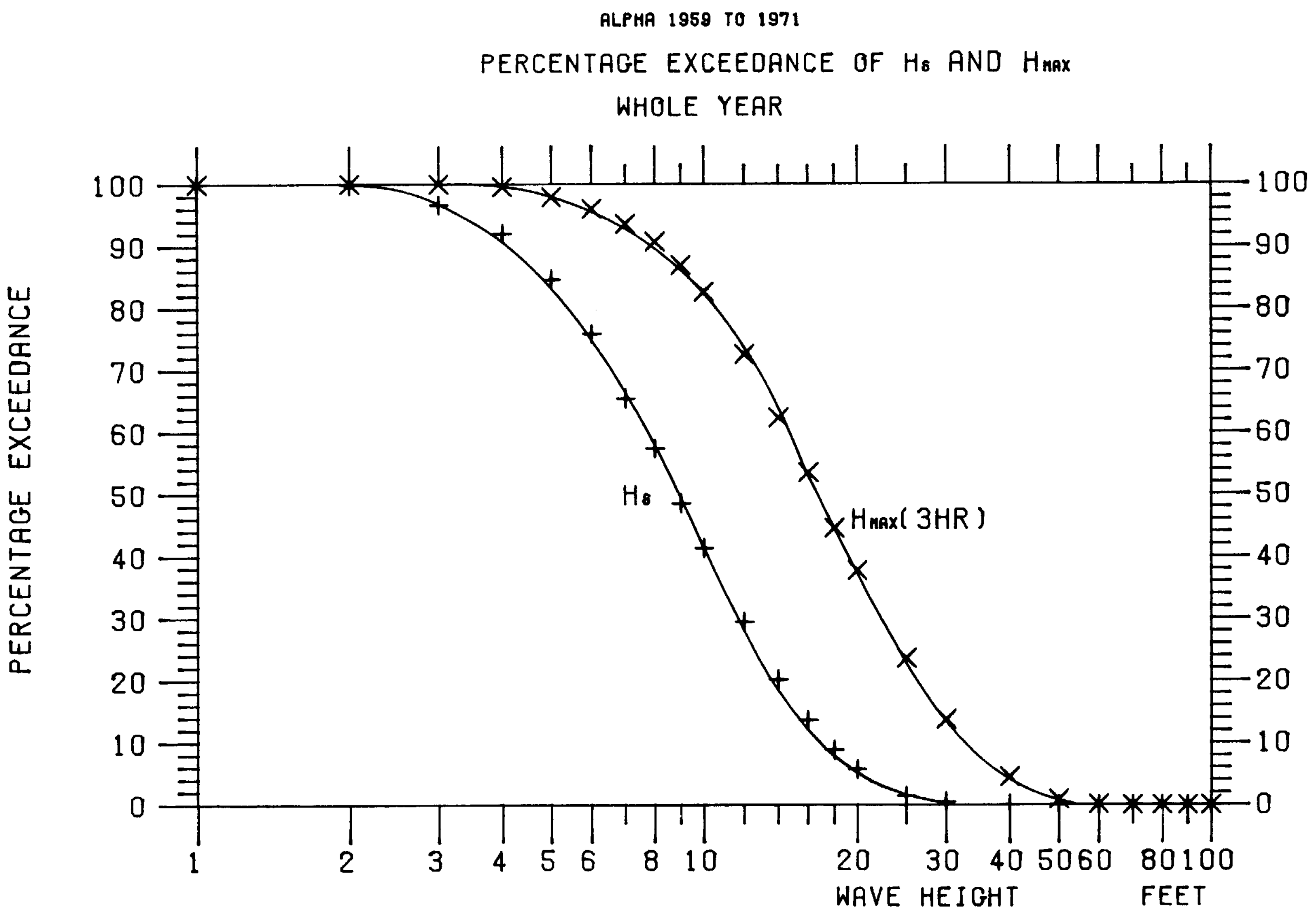
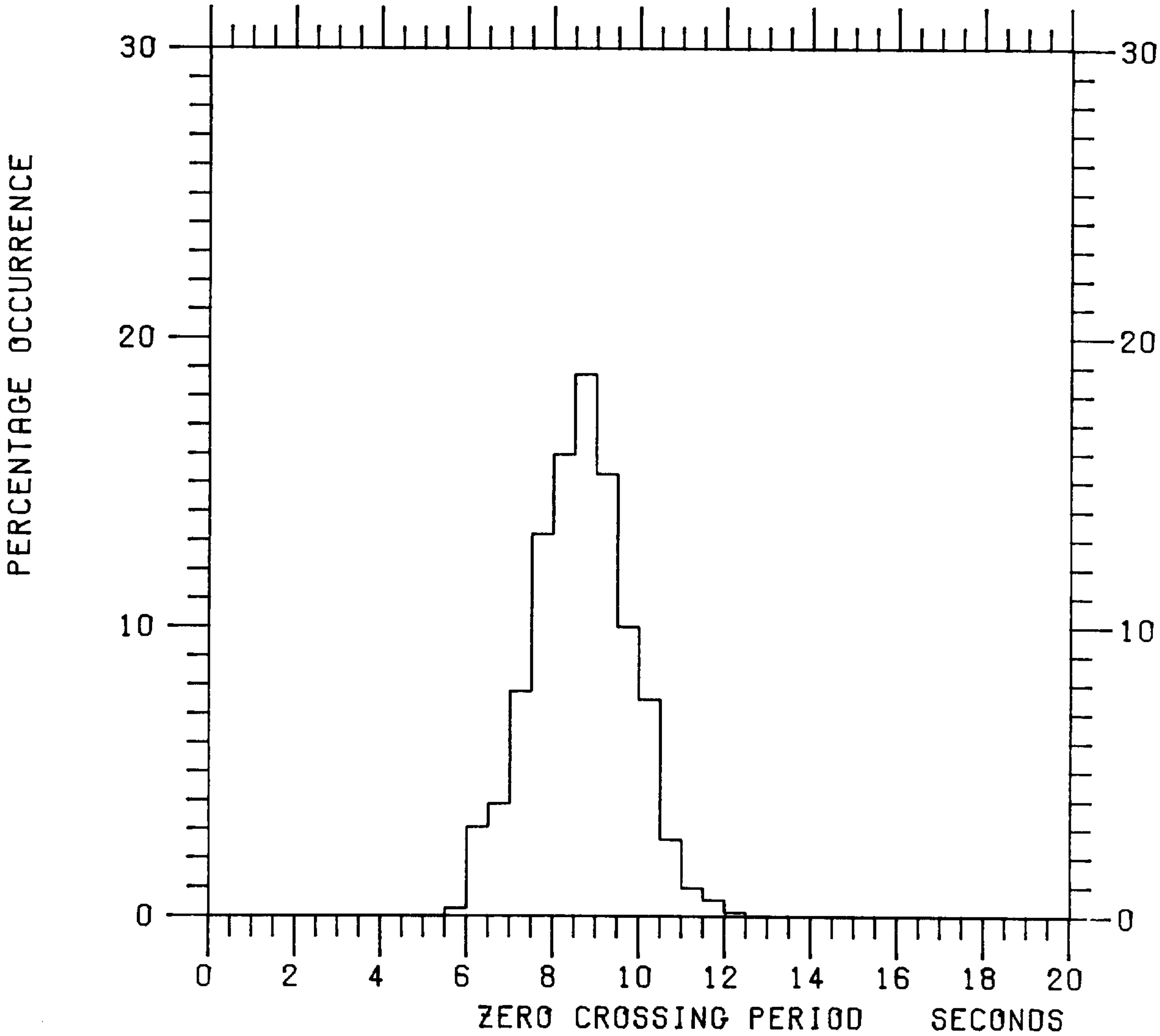

ALPHA 1959 TO 1971
PERCENTAGE EXCEEDANCE OF Hs AND Hmax
WHOLE YEAR
PERCENTAGE EXCEEDANCE
100
90
80
70
60
50
40
30
20
10
0
Hs
Hmax(3HR)
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
WAVE HEIGHT
FEET

FIG. 5

ALPHA 1959 TO 1971

PERCENTAGE OCCURRENCE OF T_z

WINTER - JANUARY TO MARCH



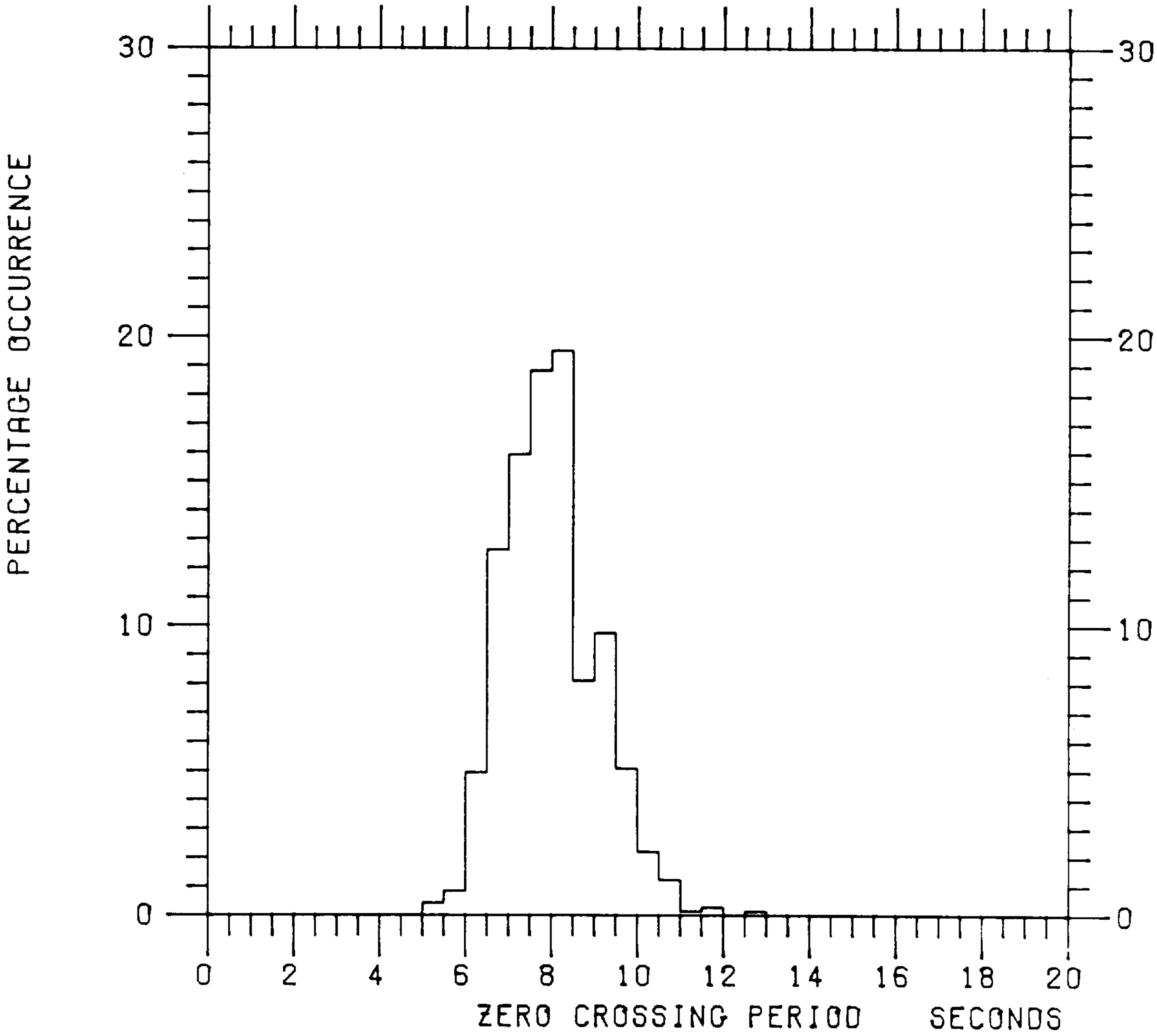
CALM= 0.00 PER CENT

FIG.6

ALPHA 1969 TO 1971

PERCENTAGE OCCURRENCE OF T_z

SPRING - APRIL TO JUNE



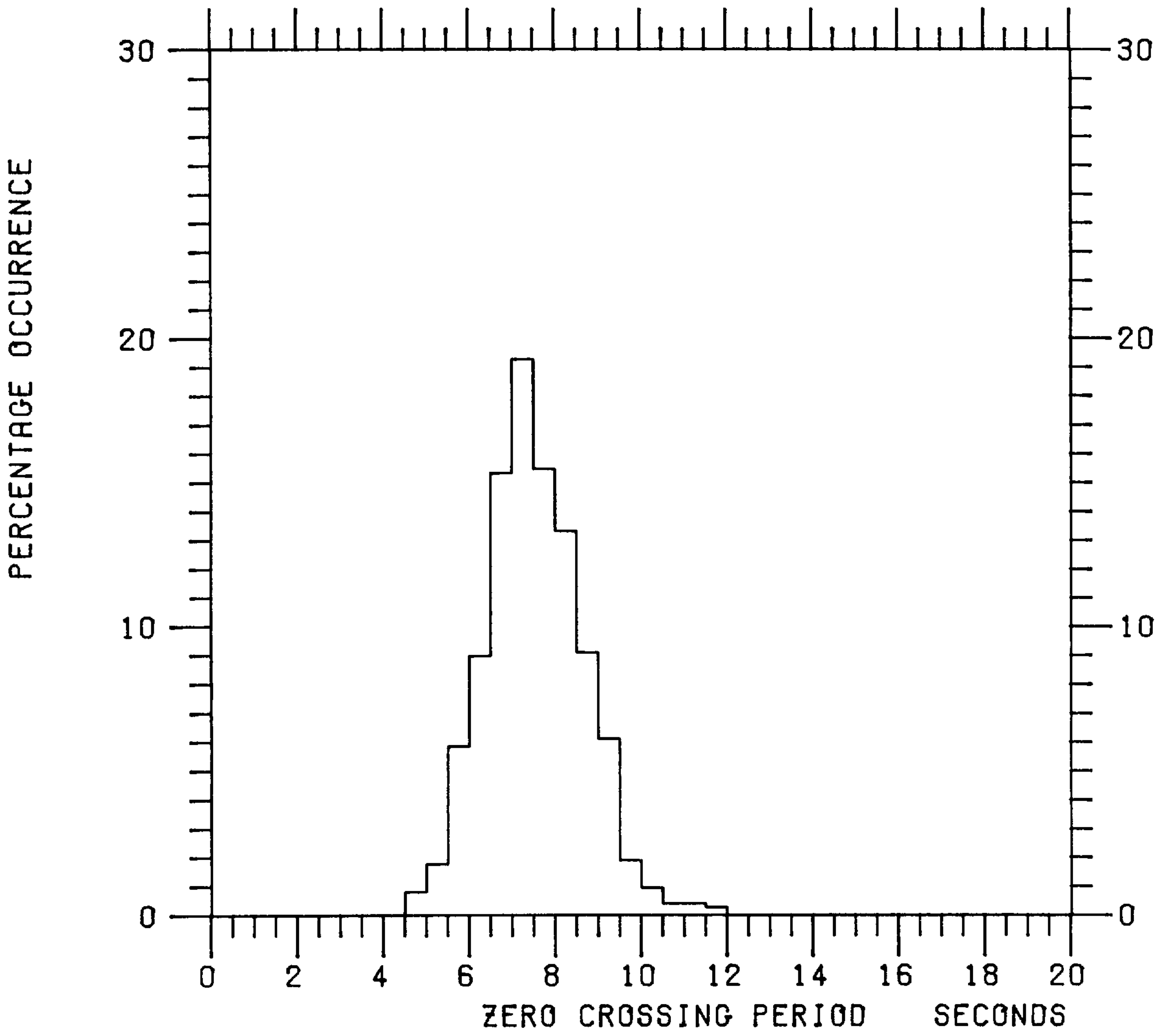
CALM= 0.00 PER CENT

FIG.7

ALPHA 1959 TO 1971

PERCENTAGE OCCURRENCE OF Tz

SUMMER - JULY TO SEPTEMBER



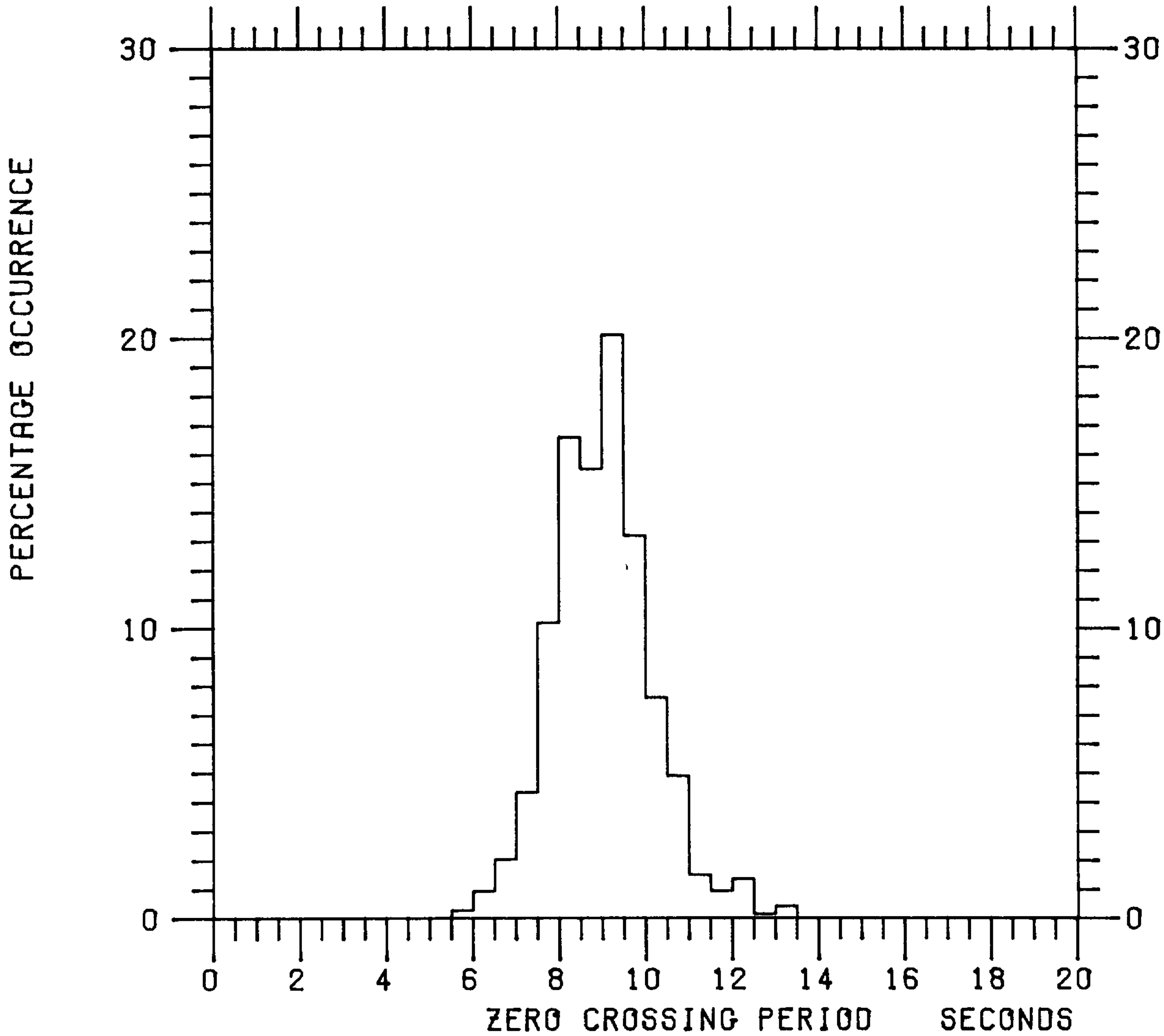
CALM= 0.00 PER CENT

FIG.8

ALPHA 1959 TO 1971

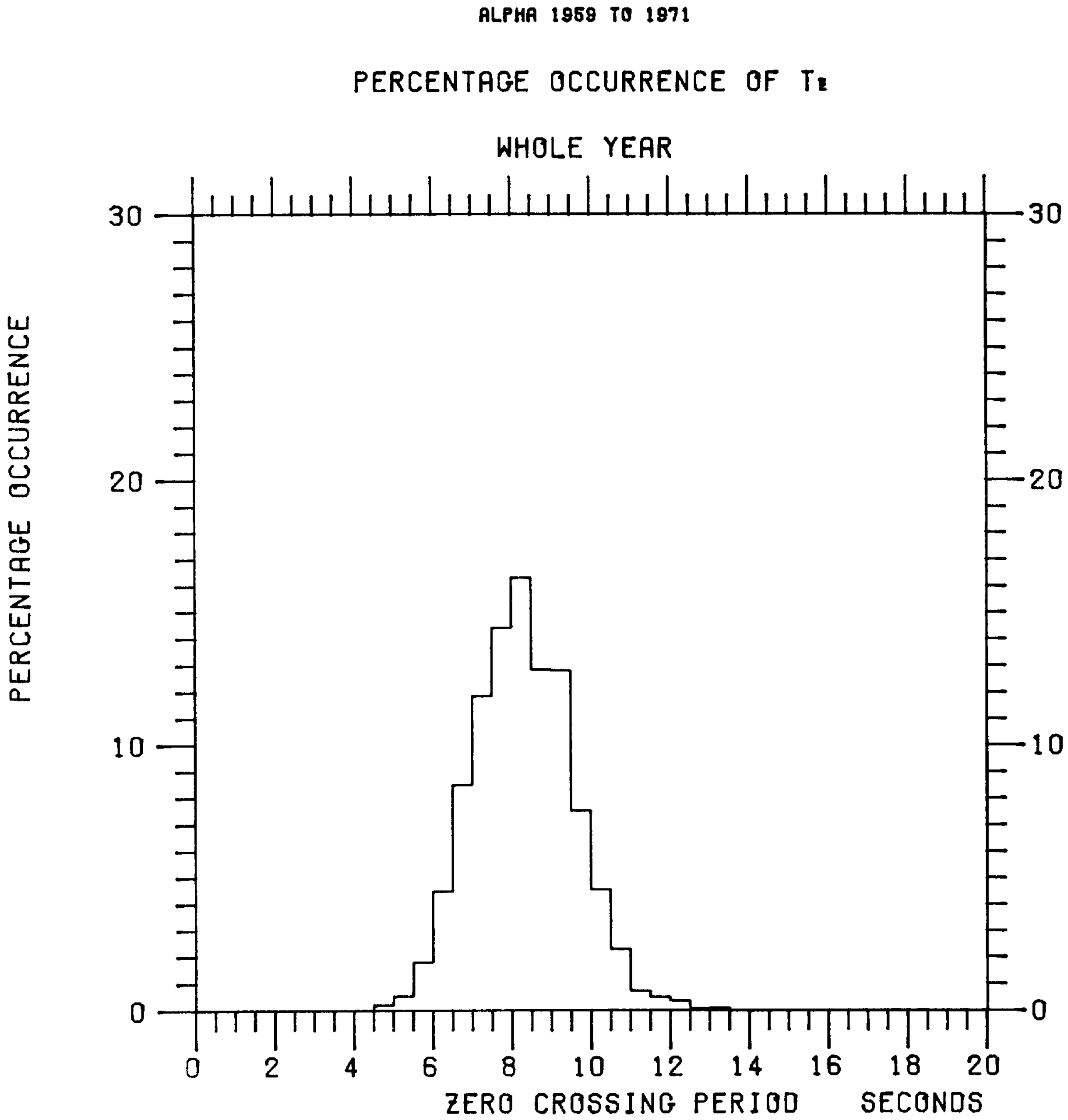
PERCENTAGE OCCURRENCE OF T_z

AUTUMN - OCTOBER TO DECEMBER



CALM= 0.00 PER CENT

FIG. 9



CALM= 0.00 PER CENT

FIG. 10

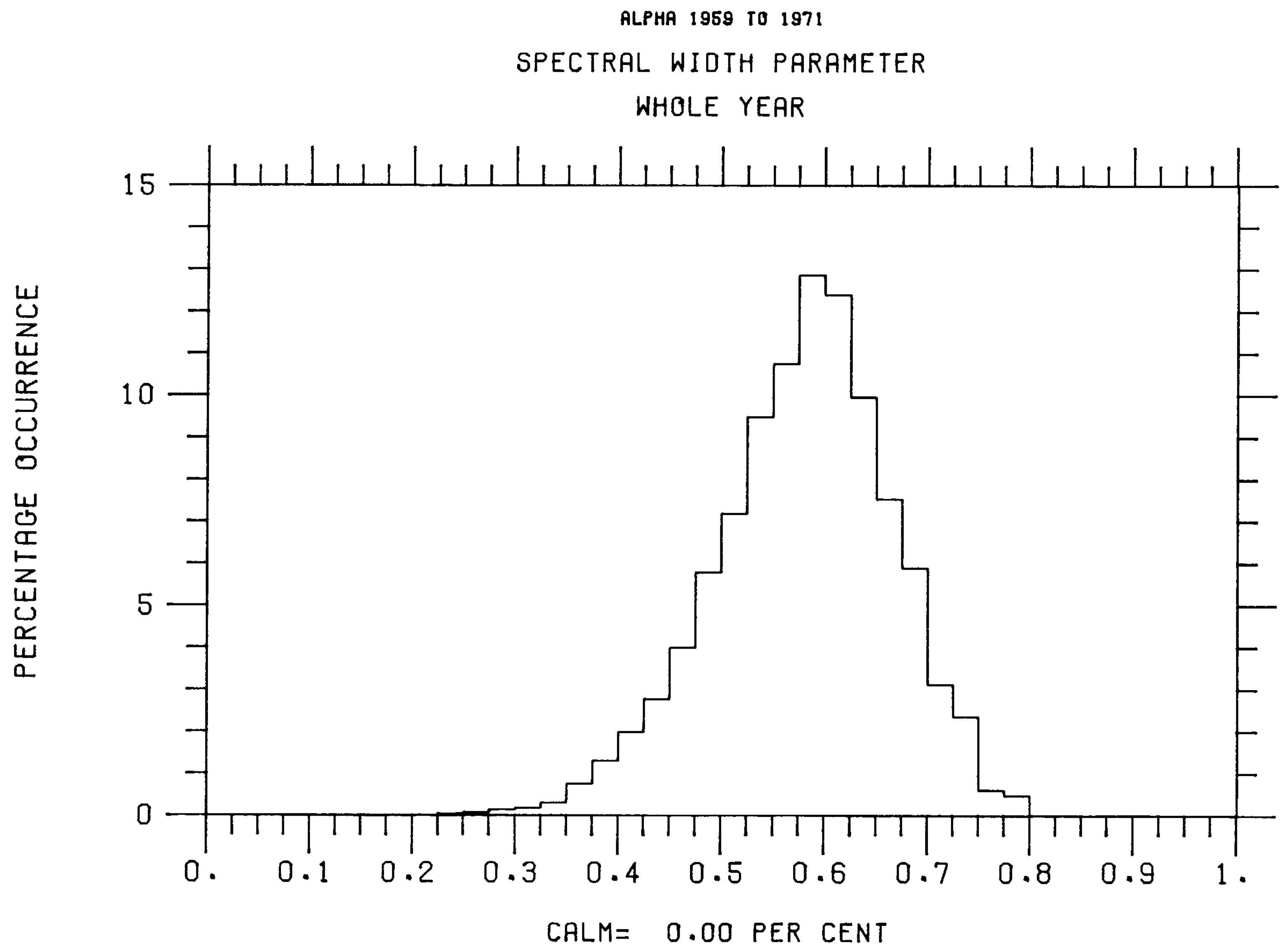

ALPHA 1959 TO 1971
SPECTRAL WIDTH PARAMETER
WHOLE YEAR
PERCENTAGE OCCURRENCE
15
10
5
0
0.
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.
CALM= 0.00 PER CENT

FIG.11

ALPHA 1959 TO 1971

SCATTER DIAGRAM FOR WHOLE YEAR

IN PARTS PER 1000 *=1 OCCURRENCE +=2 OCCURRENCES

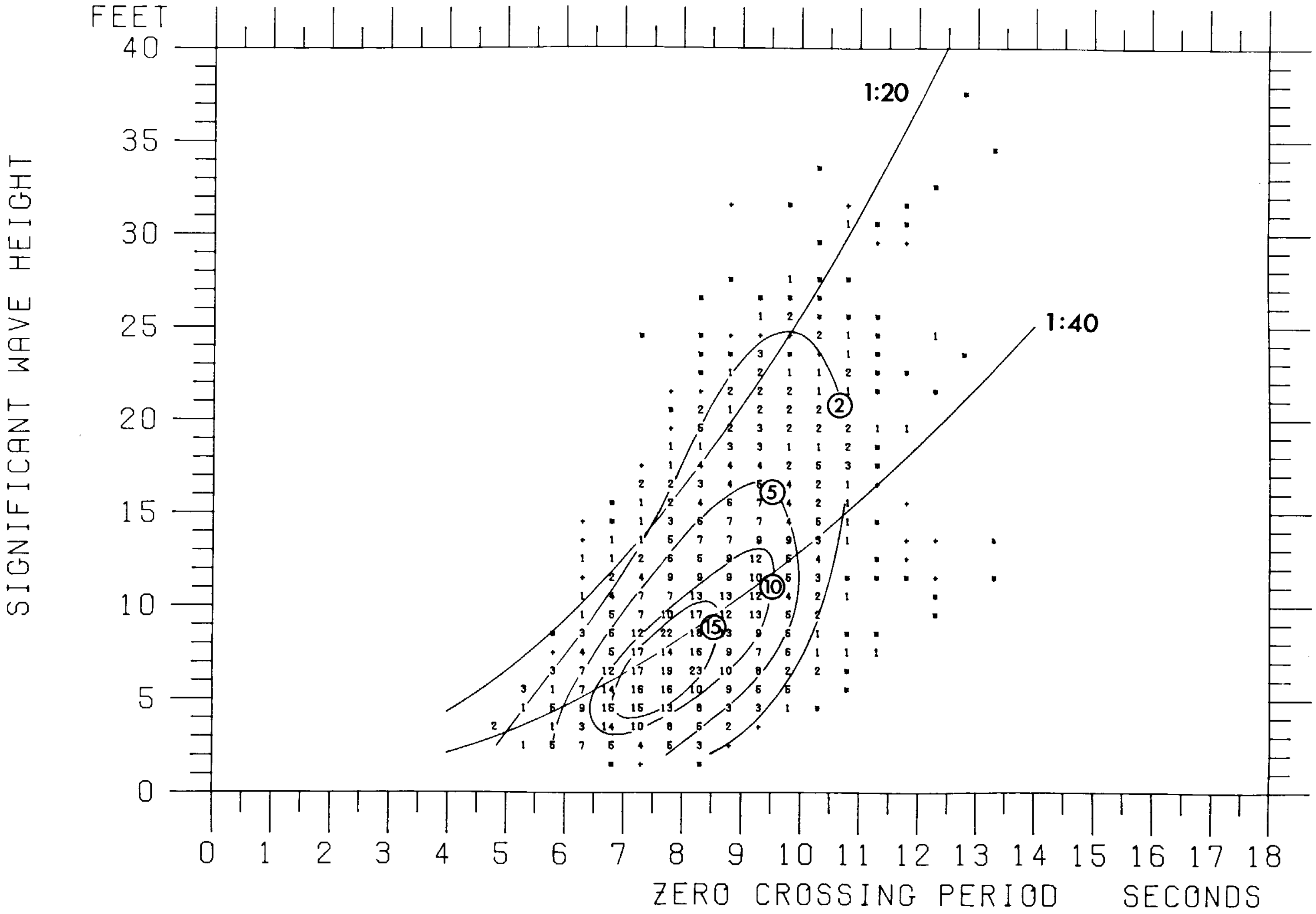


FIG. 12

ALPHA S.B.W.R. DATA. 1959 TO 1971

CUMULATIVE DISTRIBUTION -WHOLE YEAR-

LOG-NORMAL DISTRIBUTION

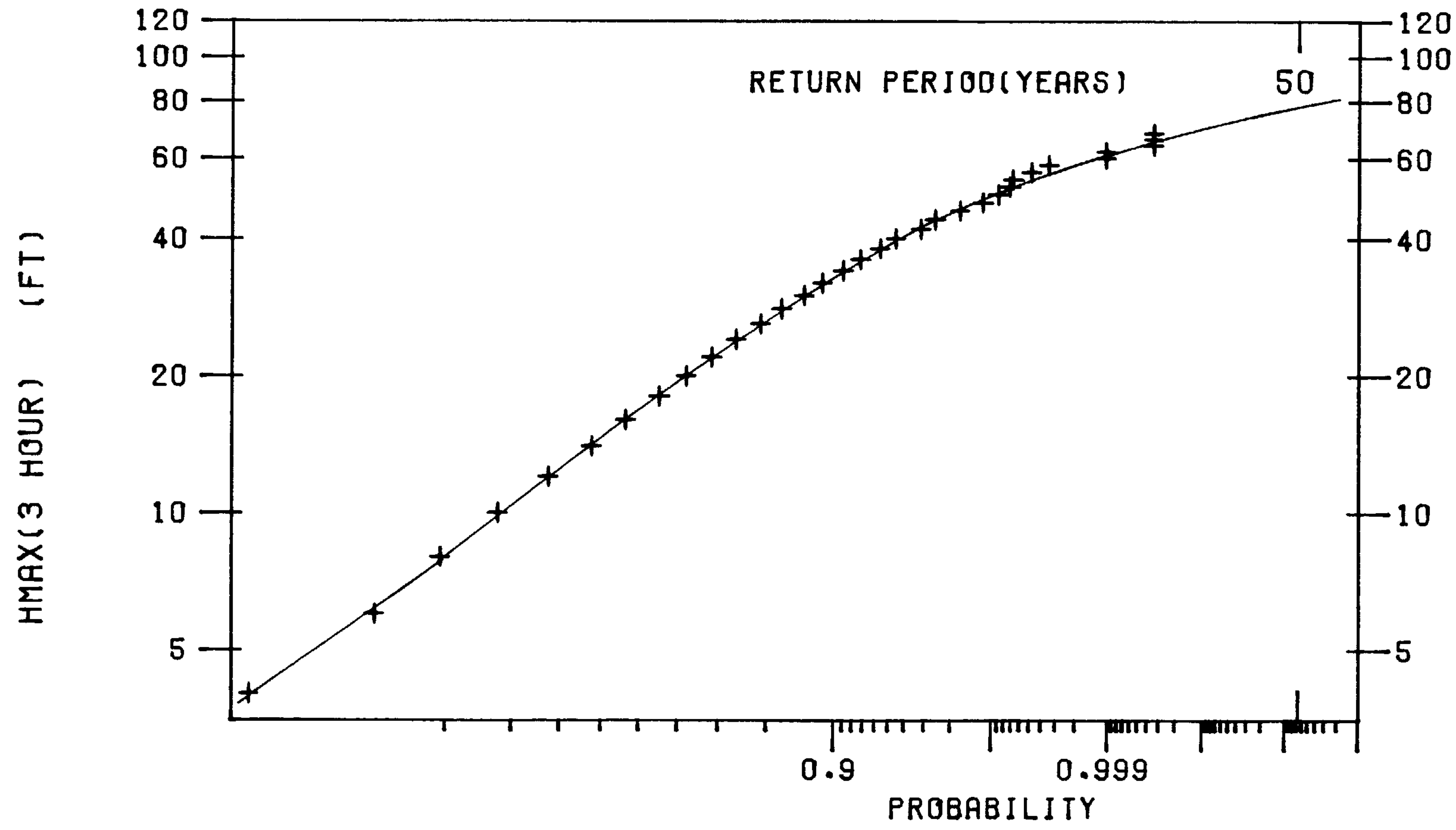
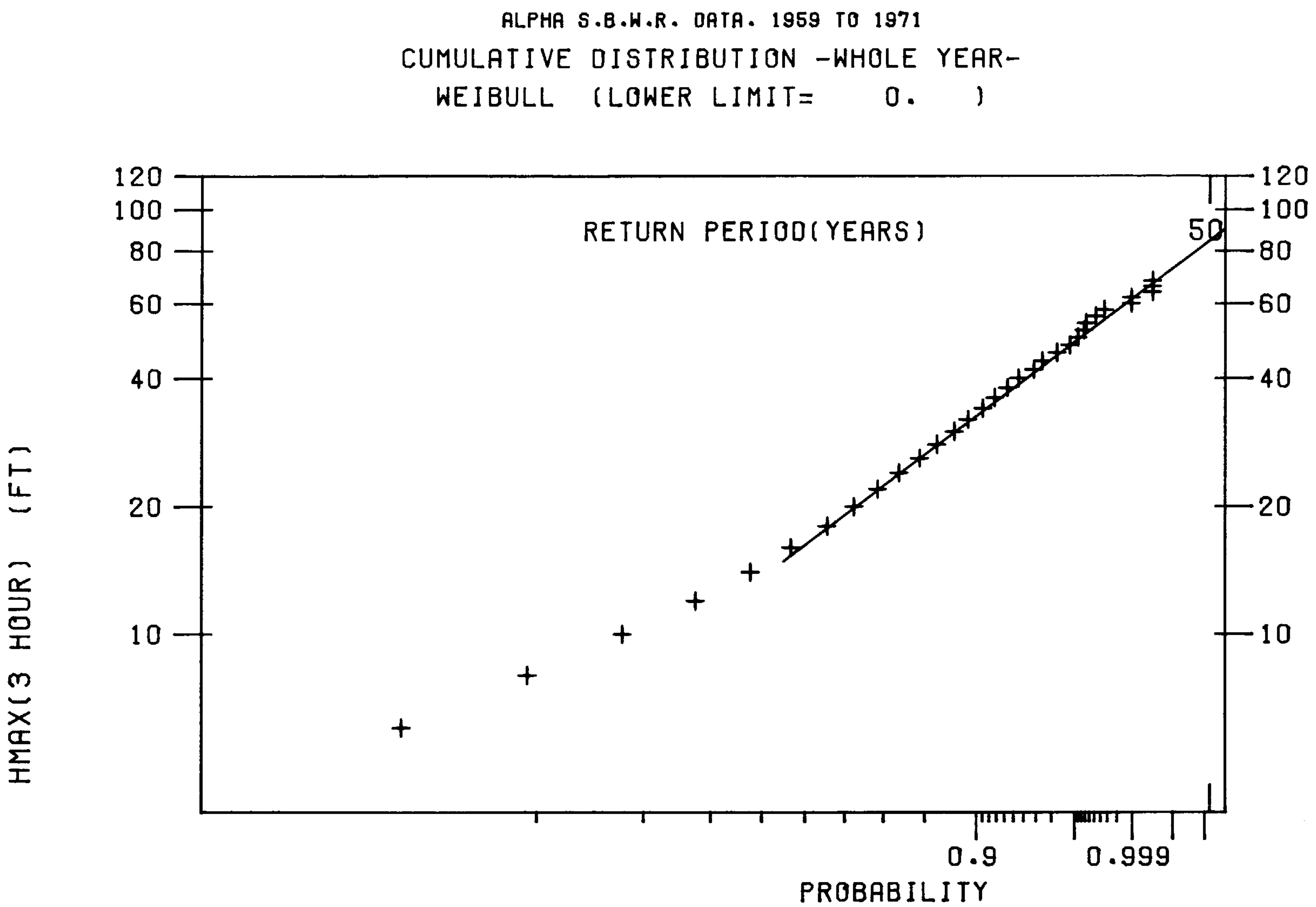


FIG. 13


ALPHA S.B.W.R. DATA. 1959 TO 1971
CUMULATIVE DISTRIBUTION -WHOLE YEAR-
WEIBULL (LOWER LIMIT= 0.)
RETURN PERIOD(YEARS)
50
HMAX(3 HOUR) (FT)
120
100
80
60
40
20
10
0.9
0.999
PROBABILITY
FIG. 14

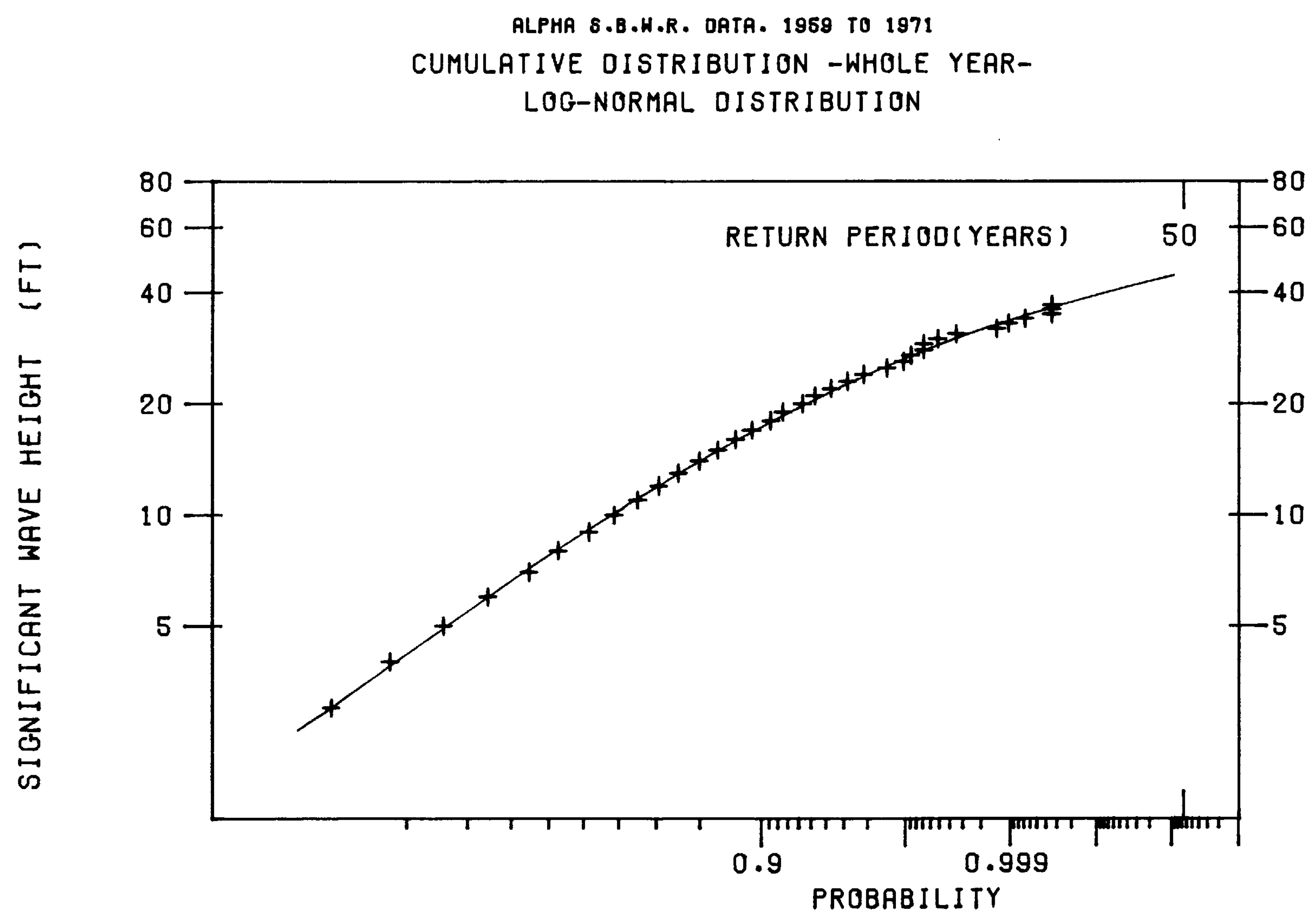

ALPHA S.B.W.R. DATA. 1969 TO 1971
CUMULATIVE DISTRIBUTION -WHOLE YEAR-
LOG-NORMAL DISTRIBUTION
SIGNIFICANT WAVE HEIGHT (FT)
80
60
40
20
10
5
RETURN PERIOD(YEARS)
50
0.9
0.999
PROBABILITY

FIG. 15

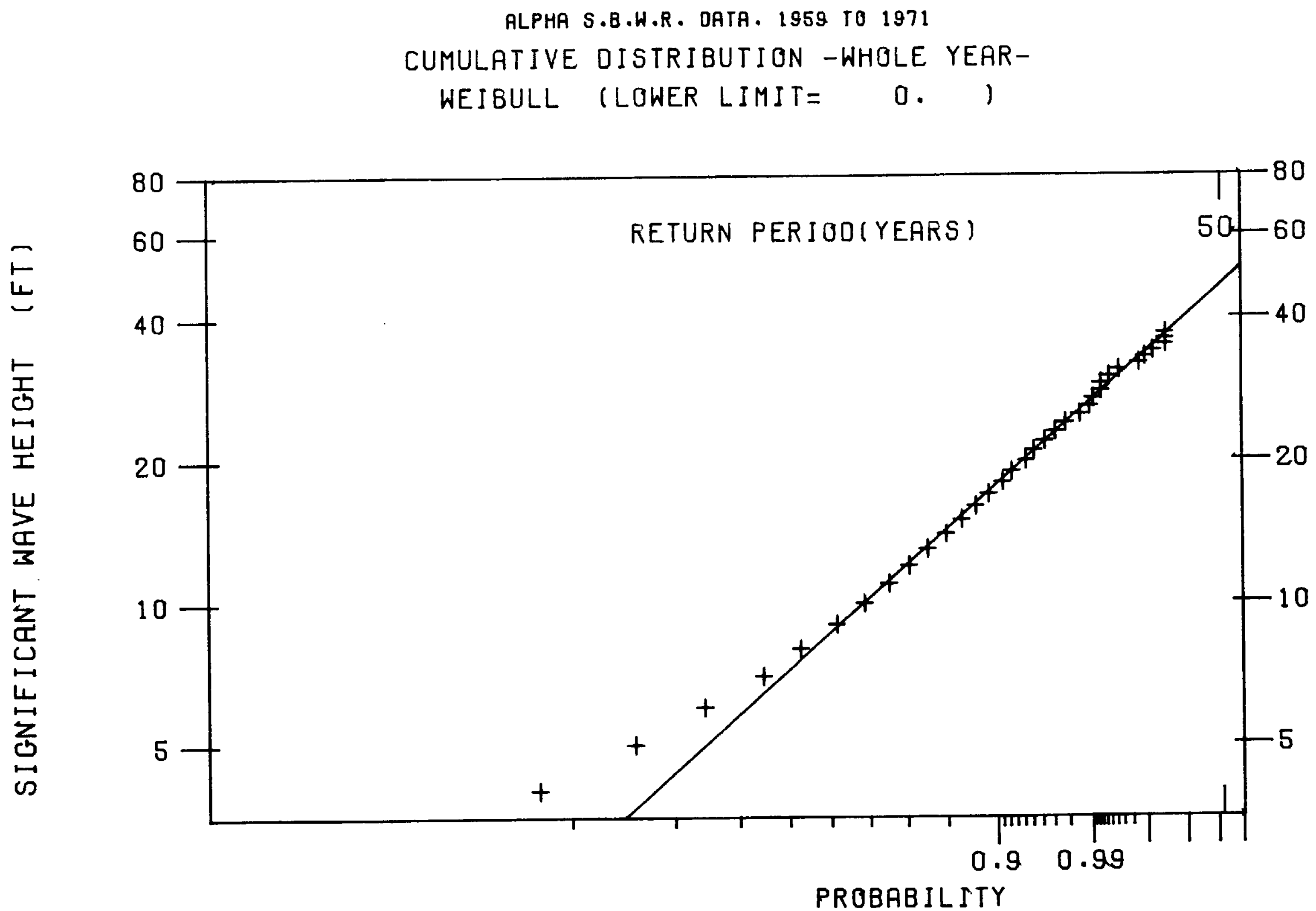

ALPHA S.B.W.R. DATA. 1959 TO 1971
CUMULATIVE DISTRIBUTION -WHOLE YEAR-
WEIBULL (LOWER LIMIT= 0.)
RETURN PERIOD(YEARS)
50
SIGNIFICANT WAVE HEIGHT (FT)
80
60
40
20
10
5
0.9
0.99
PROBABILITY

FIG. 16

ALPHA S.B.W.R. DATA. 1959 TO 1971
CUMULATIVE DISTRIBUTION -WHOLE YEAR-
WEIBULL (LOWER LIMIT= 1.400)

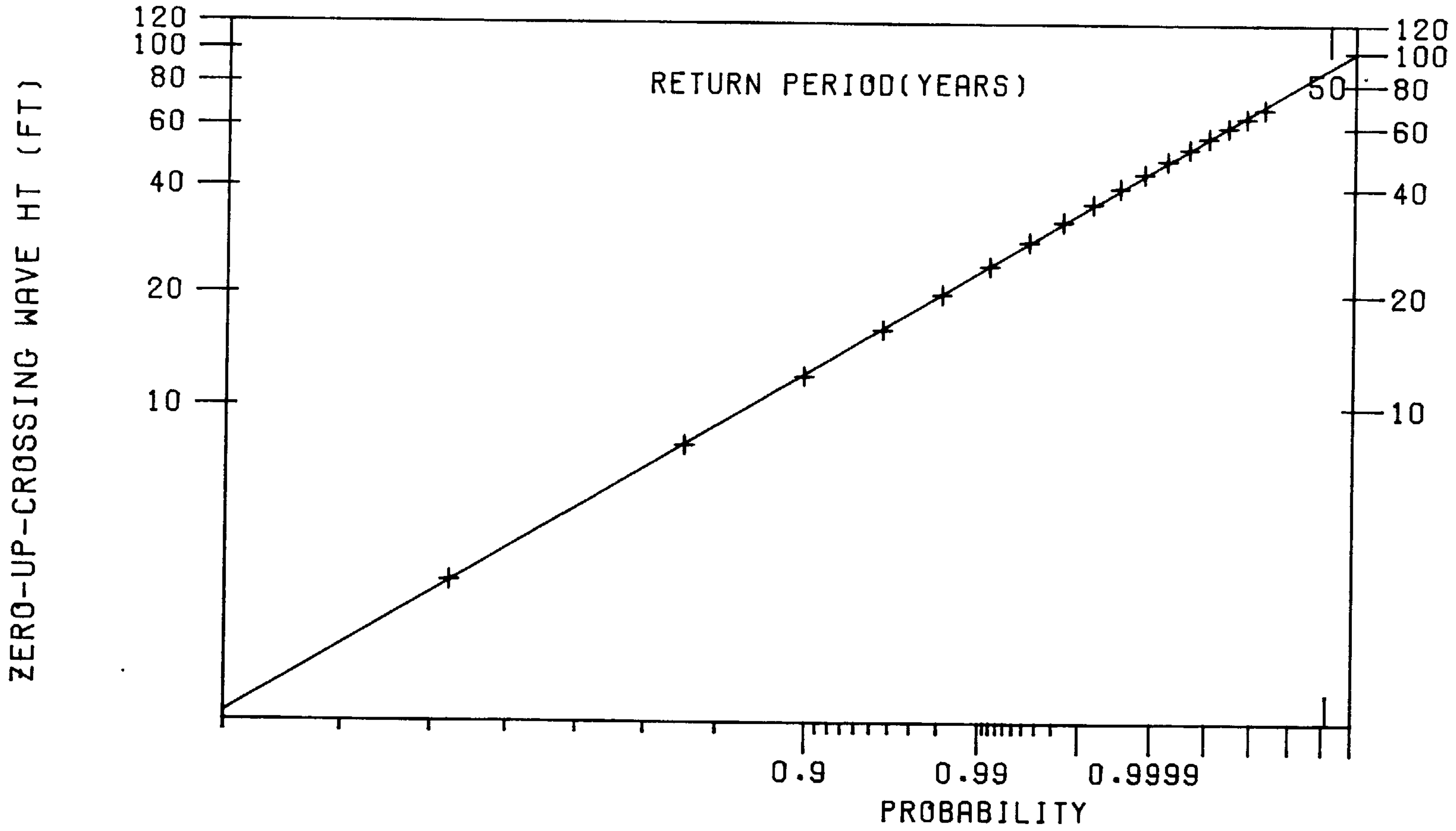


FIG.17

ALPHA S.B.W.R. DATA. 1959 TO 1971

CUMULATIVE DISTRIBUTION -WHOLE YEAR-

NEG.EXPONENTIAL

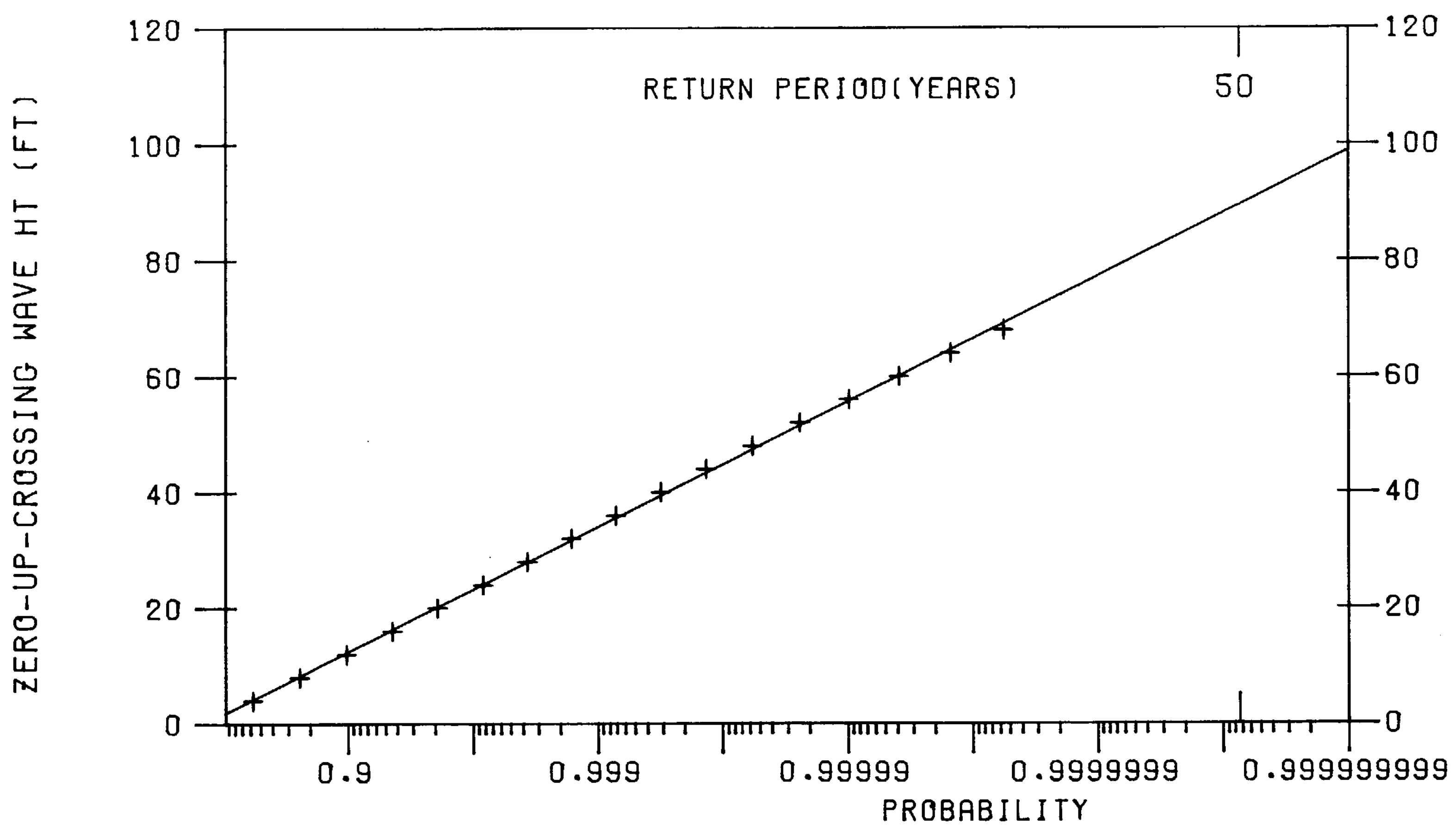


FIG. 18