WAVES AT MORECAMBE BAY LIGHT VESSEL IN 1957

L DRAPER AND D J T CARTER

SUMMARY ANALYSIS AND INTERPRETATION REPORT

REPORT NO 113
1982

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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Wormley, Godalming,
Surrey, GU8 5UB.
(0428 - 79 - 4141)

(Director: Dr. A.S. Laughton FRS)

Bidston Observatory,
Birkenhead,
Merseyside, L43 7RA.
(051 - 653 - 8633)

(Assistant Director: Dr. D.E. Cartwright)

Crossway,
Taunton,
Somerset, TA1 2DW.
(0823 - 86211)

(Assistant Director: M.J. Tucker)

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Institute of Oceanographic Sciences,
Wormley, Godalming, Surrey, GU8 5UB

Tel: Wormley (042 879) 4141
Telex: 858833

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FIGURES

WAVES AT MORECAMBE BAY LIGHT VESSEL IN 1957

by L. Draper and D.J.T. Carter

INTRODUCTION

Waves have been recorded by a Shipborne Wave Recorder (Tucker, 1956) on the Morecambe Bay Light Vessel ($53^{o}52'$N $3^{o}30'$W, about 31 km (16½ miles) west of Rossall Point, Fleetwood). The vessel was stationed in 22 m (12 fathoms) of water where the tidal range is 8.4 m (28 feet). The maximum tidal currents at mean spring tide are about 1 m/s (2 kt). The recordings started in late 1956 and continued satisfactorily until 1958. Analogue chart records from the first calendar year of operation were analyzed in a non-standard way by Jack and Mollie Darbyshire for use in the development of the Darbyshire wave forecasting method. The analytical methods now used had not then been developed, but a report on the wave climate at Morecambe Bay (Draper, 1968) was written using the data analyzed by the Darbyshires (Darbyshire, M., 1958) converted by approximate methods to the parameters now taken directly from chart records. The methods of presentation in the 1968 report were those which had by then become standardized. Since that time the need has arisen to ensure that results of the measurements are as accurate as is possible, so the records have been re-analyzed by present methods to make the results comparable in every way with other wave data reports published by I.O.S. One external consideration influenced the choice of dates of data analyzed: the Meteorological Office has wind data in computer-compatible form from Valley, Anglesey from 1 January 1957, so to enable a comparison to be made of winds during the wave recording time with winds over a longer time, the year of analysis was started from that date.

WAVE RECORDS AND THEIR ANALYSIS

The original recordings were made for radar research purposes which dictated that measurements be made every hour from 0900 to 1800 GMT, with no measurements being taken at night, so it is not possible to calculate wave persistence figures. Otherwise the standard I.O.S. wave analysis package has been used. This was designed for records at three-hourly intervals and requires eight records per day, so the Morecambe Bay records at 1100 and 1600 have been omitted from the analysis. The resulting 8 records per day were then treated as though they had been recorded at 3-hourly intervals. Although these records are more highly correlated than genuine 3-hourly records, their use should not introduce any significant bias into the results - assuming no diurnal variation in wave height - except to under-estimate slightly the 50-year return values. However, in effect it reduces the number of independent measurements, so reduces the accuracy of the estimated wave climate parameters.

From each recording of approximately 15 minutes duration the following parameters were obtained:

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

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

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 in an upward direction through the mean water level.

T_c = The mean crest period.

From these measured parameters the following values have been calculated, after allowing for instrumental response (the method is described by Tann (1976)):

H_s = The significant wave height, defined as 4σ where σ is the root mean square surface elevation. This is calculated separately from both H_1 and H_2, and an average taken.

H_{max} (3 hours) = The most likely maximum zero-up crossing wave height occurring in 3 hours, estimated from H_s and T_z assuming a Rayleigh distribution.

ε = The spectral width parameter given by $\varepsilon^2 = 1 - (T_c/T_z)^2$ (Tucker, 1961).

The results of these measurements are expressed graphically, divided into seasons thus:

Winter:	January	February	March
Spring:	April	May	June
Summer:	July	August	September
Autumn:	October	November	December

For each season a graph (Figures 1-4) shows the cumulative distributions of significant wave height H_s and of the most probable value of the height of the highest wave in the effective recording interval, H_{max} (3 hours). Figure 5 presents the same data for the whole year.

The distribution of zero-up-crossing period is given for each season (Figures 6-9). Figure 10 presents the same data for the whole year. The distribution of spectral width parameter is given for the whole year (Figure 11). Figure 12 is a scatter diagram relating significant wave height to zero-up-crossing period.

Figures 13 to 20 show various plots of H_s and $H_{max(3\ hours)}$ on log-normal and Weibull probability paper, for use in estimating 50-year return values.

Figures 21 and 22 show cumulative distributions of H_s and $H_{max(3\ hours)}$ for sea level above and below mean tide level respectively.

DISCUSSION OF RESULTS

Wind conditions

Wind measurements made at Valley, Anglesey, which is in an exposed position in the main generating area for waves at Morecambe Bay, are likely to be representative of winds over the entire fetch. The Meteorological Office has analyzed a 6-year (1957-62) series of wind measurements there, and a summary of the results is shown in Tables 1 and 2. Unfortunately the type of anemometer was changed in 1963 and there is only this 6-year sequence of wind data available for comparison.

Season	Winter	Spring	Summer	Autumn	Year
1957	13.8	9.1	11.4	12.1	11.6
Six-year average	12.1	9.6	10.3	12.1	11.0

Table 1. Average of the hourly-mean wind speeds in knots over each season and whole year of 1957 compared with a 6-year average.

Season	Winter	Spring	Summer	Autumn	Year
1957	14.6	0.9	6.7	8.2	7.6
Six-year average	8.7	2.9	4.2	10.0	6.4

Table 2. Percentage frequency of occurrence of winds of 25 knots or greater, over each season and whole year for 1957 compared with a 6-year average.

An examination of these tables shows that the year 1957 was somewhat more windy than average. The winter and summer were more severe than usual, spring was quieter, and autumn was close to average. This applied both to the mean speeds and the occurrence of higher wind speeds. However, it must be remembered that the average values are computed from only six years' data and do not adequately represent a long-term average.

Wave data

From Figures 1-5 may be determined the proportion of time for which H_s or $H_{max(3\ hours)}$ exceeded any given height. For example, in the autumn of 1957 the significant wave height exceeded 2 metres for 26% of the time, in the summer of 1957 that height was exceeded for 21% of the time, whereas in the spring of 1957 that height was exceeded for only 5% of the time. It seems likely that in 1957 the spring wave conditions were less severe and the summer more severe than average.

It is not advisable to expect a high correlation between wind and wave climates over short lengths of time such as a season, because differences in wind duration, changes of direction, as well as the distribution of wind with respect to direction, can result in a considerably different wave climate for a given mean wind speed. However, for operational purposes it would probably be sensible to alter the wave heights by a factor related to the difference from normal of the mean wind speed for each season, and it is recommended that the wave heights given in this report be modified by the following factors:

Winter	Spring	Summer	Autumn	Year
0.82	1.08	0.86	1.00	0.92

These are based on the assumption that wave height is related to the wind speed to the power 1.5 (Darbyshire, J., 1961).

Because of the very small number of occurrences of high wind speeds it is not, however, sensible to make any additional numerical alteration to high wave heights based on the differences of high winds from normal. It is sufficient to observe that the occurrence of high winds quantified as wind speeds of 25 knots and above (about force 6) was also high in 1957 compared with the long term average. These differences in wind speeds are within the expected variations from year to year.

Figures 6-10 show that the zero-up-crossing periods lay between 3 and 9 seconds. There was little variation throughout the year, the modal value was generally between 4 and 5 seconds. The only exception being winter, a time of higher winds, when the periods lengthened a little to give a modal value of over 5 seconds.

Figure 11 shows the spectral width parameter ε to vary from 0 to 0.7. The value of $\varepsilon = 0$ indicating that the number of crests and zero-up-crossings are equal, has rarely been found on wave records from other sites. Its occurrence at Morecambe Bay is possibly due to the relatively enclosed site, with swell only able to enter through the narrow gaps of St. George's and North Channel, or, in the case of the shorter period low height waves, due to the filtering action of the instrument and pen recorder artificially producing a narrow band. The wave periods associated with $\varepsilon = 0$ range from 3.5s to 7.1s, and significant wave height steepness from 1 : 20 to 1 : 275.

Figure 12, the bi-variate height and period distribution, or scatter diagram, relates the significant wave height to zero-up-crossing wave period, with the occurrences expressed in parts per thousand. There are 2648 records, out of a possible 2920, represented on this diagram. Where there are only one or two occurrences of a particular combination of height and period, yielding less than one part per thousand, the actual number of occurrences is given and is underlined. As an example, the most commonly occurring wave conditions were those between 4 and 4.5 seconds and with a height between 0.5 and 1 metre, and also between 1 and 1.5 metres, both of which occurred for 43 thousandths, or 4.3 percent, of the time. However, several other adjacent combinations of height and period were not significantly different in occurrence as can be seen on the diagram. The absence of wave periods below 3 seconds is due to the attenuation of waves with depth; this was because the instrument's pressure unit sensors were situated about 1.8 metres below mean water level.

A parameter which is sometimes of interest is wave steepness, expressed as wave height : wave length. It should be noted that steepness is not the same as the maximum slope of the water surface during the passage of a wave. Curves corresponding to waves of constant steepness of between 1 : 7 and 1 : 40 are drawn on Figure 12. (Wave length L was computed using linear wave theory with the waves, of period T, in deep water; that is $L = gT^2/2\pi$). The figure indicates some waves of unusually high steepness, probably due to the occurrence of currents approaching 1 m/sec (two knots) at spring tides.

The highest value of H_s obtained from the presented data set was 5.3 m which occurred at 1000 on 8 December 1957 with an associated T_z of 6.8 seconds. However, on the same day the unused records (at 1100 and 1600 hours) showed one example of H_s of 5.9 m with T_z = 6.61 sec. This record contained the highest wave measured in the year which had a true value of H_1 of 9.0 m (when corrected for instrumental response). On 25th August 1957, significant wave heights were close to 4.7 m on three occasions.

EXTREME VALUES

The 50-year return values of significant wave height and of $H_{max(3\ hours)}$ are estimated by fitting a probability distribution to the cumulative statistics of the data and extrapolating into the upper tail of the distribution to a probability corresponding to the required return value.

There is no theoretical or physical justification for using any particular probability distribution, but in practice either the log-normal or the Weibull distribution generally appear to fit. Both distributions are used in this report.

A particular problem with the analysis of the Morecambe Bay data set is that it comes from observations made at hourly intervals, so the data are strongly correlated. The effect of this correlation is to produce an apparent reduction in the tails of the fitted distribution and hence to underestimate low-probability return values. (Usually, wave data are obtained at three-hourly intervals and are assumed to be independent). In order to investigate the magnitude of the under-estimation, a data set of three-hourly values - from the measurements at 0900, 1200, 1500 and 1800 GMT - has been analysed, as well as the complete data set.

Figures 13 to 16 show the log-normal and Weibull fits to the complete data set. Corresponding 50-year return values are given in Table 3, together with return values corrected by mean wind speeds to allow for wind conditions during the year of observation.

Figure			Basic	Wind Corrected
13	Significant Wave Height	log-normal	7.0 m	6.4 m
15	" " "	Weibull	6.9 m	6.3 m
14	Maximum " "	log-normal	13.0 m	12.0 m
16	" " "	Weibull	13.2 m	12.1 m

Table 3. 50-year values of wave height for the highly correlated eight samples per day. 'Basic' implies not corrected for mean wind speed.

Clearly the points in Figures 13 and 15 do not lie on a straight line, indicating that the data do not have a log-normal distribution - although the distribution of the upper values might approximate to one.

Figures 17 and 18 show the cumulative statistics of the three-hourly data sets of H_S and $H_{max(3\ hours)}$ plotted on Weibull probability paper. Corresponding 50-year return values are given in Table 4.

Figure			Basic	Wind Corrected
17	Significant Wave Height	Weibull	7.6 m	7.0 m
18	Maximum Wave Height	Weibull	14.2 m	13.1 m

Table 4. 50-year values of wave height for the relatively uncorrelated four-per-day samples. 'Basic' implies not corrected for mean wind speed.

Using the method proposed by Battjes (1970) for estimating the 50-year return value of individual zero-up-crossing wave heights, assuming these heights have a three-parameter Weibull distribution, gives a value of 14.2 m when applied to the 3-hourly data set. Fitting a negative exponential distribution gives 14.1. These values, which are not corrected for wind speed, seem consistent with those obtained by other approaches.

Seasonal variations

The wind corrections applied to the return values in Tables 3 and 4 are based upon the average difference from mean conditions throughout the year of observation. However, the correction factors show considerable variation from season to season; in particular, summer 1957 was more windy than the average summer over the years 1957-1962. Examination of the Morecambe Bay wave data for 1957 shows heights during August and September which are comparable to those measured during the autumn and winter, in agreement with evidence from the wind data that the summer of 1957 contained some unusually rough spells.

This inference is supported by the description of the conditions for August 1957 in the Royal Meteorological Society's magazine 'Weather' (1957). During much of the first fortnight there was considerable thundery activity and heavy falls of rain, with 48.5 mm (1.91 in) falling at Colwyn Bay (on the North Wales coast) during 11th August. Later in the month an intense depression affected the UK during which "pressure fell to a new low record for August over the British Isles of 966 mb, there were gales and heavy rain in Wales and many northern districts. At Ronaldsway, 81 mph (130 kph) was recorded in squalls and Stornoway had 2.25 inches (57 mm) of rain on the 25th."

Estimates of 50-year return values of H_s for each season have been obtained by fitting a two-parameter Weibull distribution to the three-hourly data set for each season. Plots are shown in Figure 19. The low waves (with H_s less than about 1 m) clearly do not have a Weibull distribution - possibly because the Shipborne Wave Recorder is poor at resolving very low, short period waves - but the higher values for each season appear to fit the distribution well.

Table 5 lists the 50-year return values of H_s for each season, and shows that the highest seasonal 50-year return value, of 7.8 m, was obtained during the summer! This indicates again the unusual nature of summer 1957 - and illustrates the limitations of estimating 50-year return values from one year's data.

Season		Return Value
Winter	(January-March)	7.0 m
Spring	(April-June)	4.8 m
Summer	(July-September)	7.8 m
Autumn	(October-December)	7.0 m

Table 5. 50-year values of H_s during each season. These values are uncorrected for wind speed.

The 50-year return value for spring (April to June) seems very low compared with values for the other seasons, possibly because wind speeds were on average lower than usual for that season; also there were no wave data for the first half of April when higher waves might have been expected.

For the 50-year return value for the entire year, it would seem reasonable to assume that the rough summer and the relatively calm spring to some extent compensate each other.

Effect of changes in tidal level

Another problem when analysing the Morecambe Bay data for extreme values is the relatively shallow water depth, particularly at low tide.

To investigate whether water depth has a significant effect on extreme conditions, Weibull distributions were fitted to the two separate data sub-sets obtained from the entire data set, one with the water depth above mean tidal level and the other with it below mean tidal level. The results are plotted in Figure 20 which clearly shows two different distributions. The 'Above' data appears to have a Weibull distribution - with a fifty-year return significant wave height value of 7.4 m.

The 'Below' data seems not to be from a Weibull and looks as if it might have an upper limit, suggesting that a Fisher-Tippett Type III distribution might be appropriate. This is assumed to be due to the influence of the sea bed upon the lower frequency, longer wavelength components.

An analysis using a proportional hazards model (McCullagh, 1980) indicates the 50-year return value of the 'Below' data corresponds to a 20-year return value of the 'Above' data which - from the Weibull distribution - is 7.1 m. This model, which only assumes a simple connection between the two distribution functions, gave a satisfactory fit.

A further problem is that the predicted wave heights for 'Below' tidal mean are likely to apply to some value of water depth intermediate between mean tide and low tide, and probably nearer to mean tidal depth. Similarly, the 'Above' tide values should be appropriate to a water depth just above mean tidal depth. It is therefore reasonable to argue that at very low tides the most severe waves would be lower than at other times; the problem is to quantify this amount. Unfortunately, the number of wave measurements made when the water depth was close to a high or low spring tidal level are too few to quantify the magnitude of the reduction with any degree of certainty but the mathematical calculation referred to above suggests a reduction in 50-year return value of significant wave height when sea level is below mean of about 0.3 m. Although there seems to be a real reduction in extreme wave height with lower mean water depths, a reduction of 0.3 m is well within the error range of the complete measurement and analysis undertaken in this study.

Even though the 'Above' data show no effect of being limited by the water depth, the extrapolated values could still be affected but they are impossible to quantify. The 50-year return value would result from a local storm with relatively unimportant swell component, so it seems prudent to use the extrapolated value; this implies a value of $H_{max(3\ hours)}$ of about 14 m being unaffected by a water depth of 26-30 m.

Summary and conclusions on extreme conditions

Estimating 50-year return values of wave height from the Morecambe Bay measurements of 1957 is especially difficult because the year appears to have been unusual, with a particularly stormy summer, whilst the wind information available to adjust for this is limited to only six years. Moreover, the wave height distribution appears to be affected by the water depth, varying with the state of the tide.

Analysis of the full data set of relatively highly-correlated hourly measurements should theoretically lead to higher estimates of low-probability return values than that from three-hourly measurements. A comparison of Tables 3 and 4 shows this to be so. Although based upon fewer measurements the results from the three-hourly measurements are to be preferred. In addition, the Battjes technique yields virtually the same result.

The average value of the hourly-mean wind speed for 1957-1962 was 5% lower than the average in 1957, suggesting that wave heights were generally about 8% higher than normal in 1957; the values corrected accordingly have been included in Tables 3 and 4. However, the assessment of average conditions from only six years of data is regarded by the Meteorological Office as rather unsatisfactory, and it seems prudent to take the uncorrected wave heights.

Therefore the proposed 50-year return value of $H_{max(3\ hours)}$ is 14.2 m and of H_s is 7.6 m.

The analysis indicates that return heights at low water are lower, with values of about 13.6 m and 7.3 m respectively. However, such corrections are small compared with the uncertainties inherent in these estimates.

ACKNOWLEDGEMENTS

The wind data used in this study were kindly provided by the Meteorological Office, and the calculations of tidal levels were kindly undertaken by IOS Bidston.

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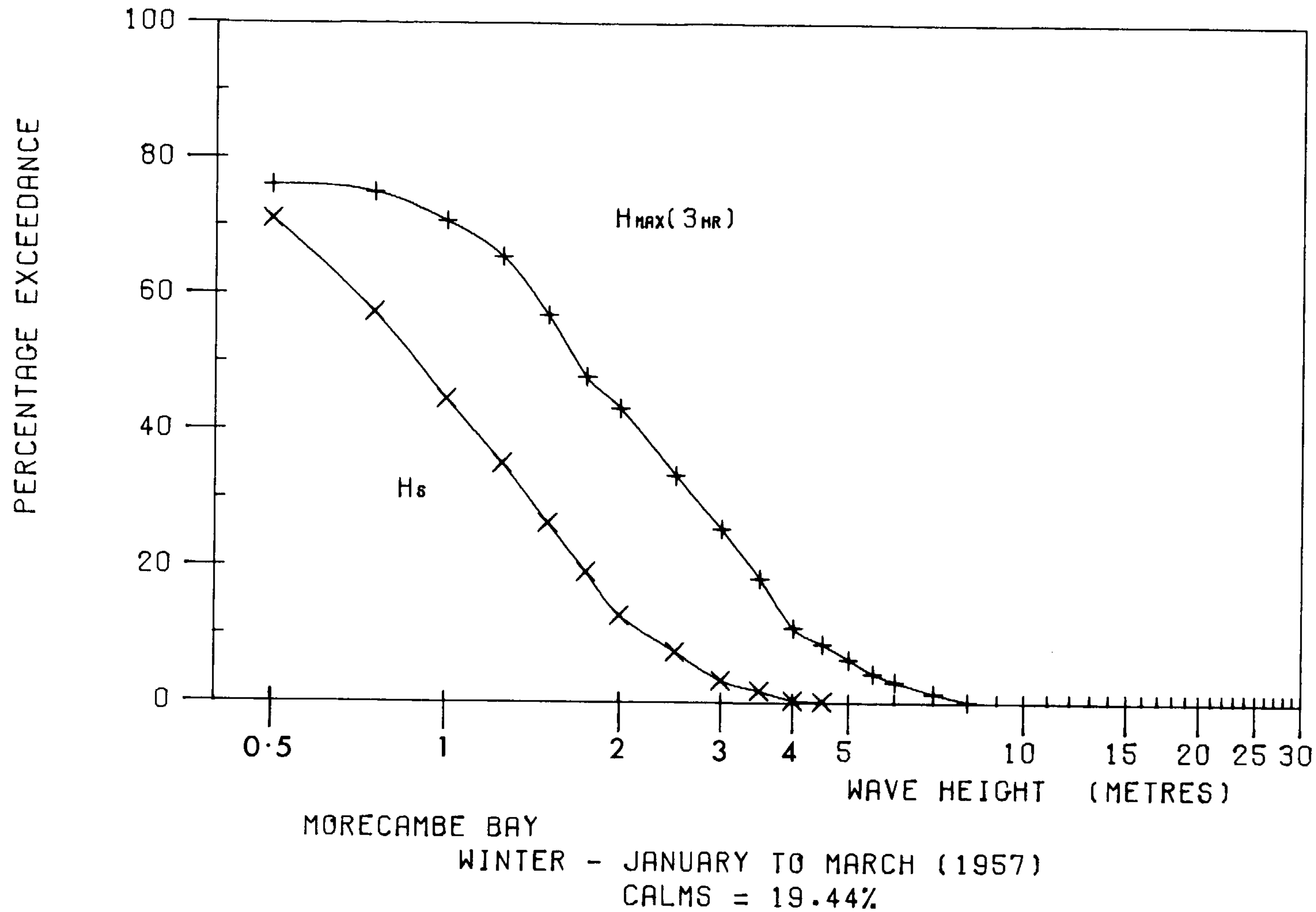
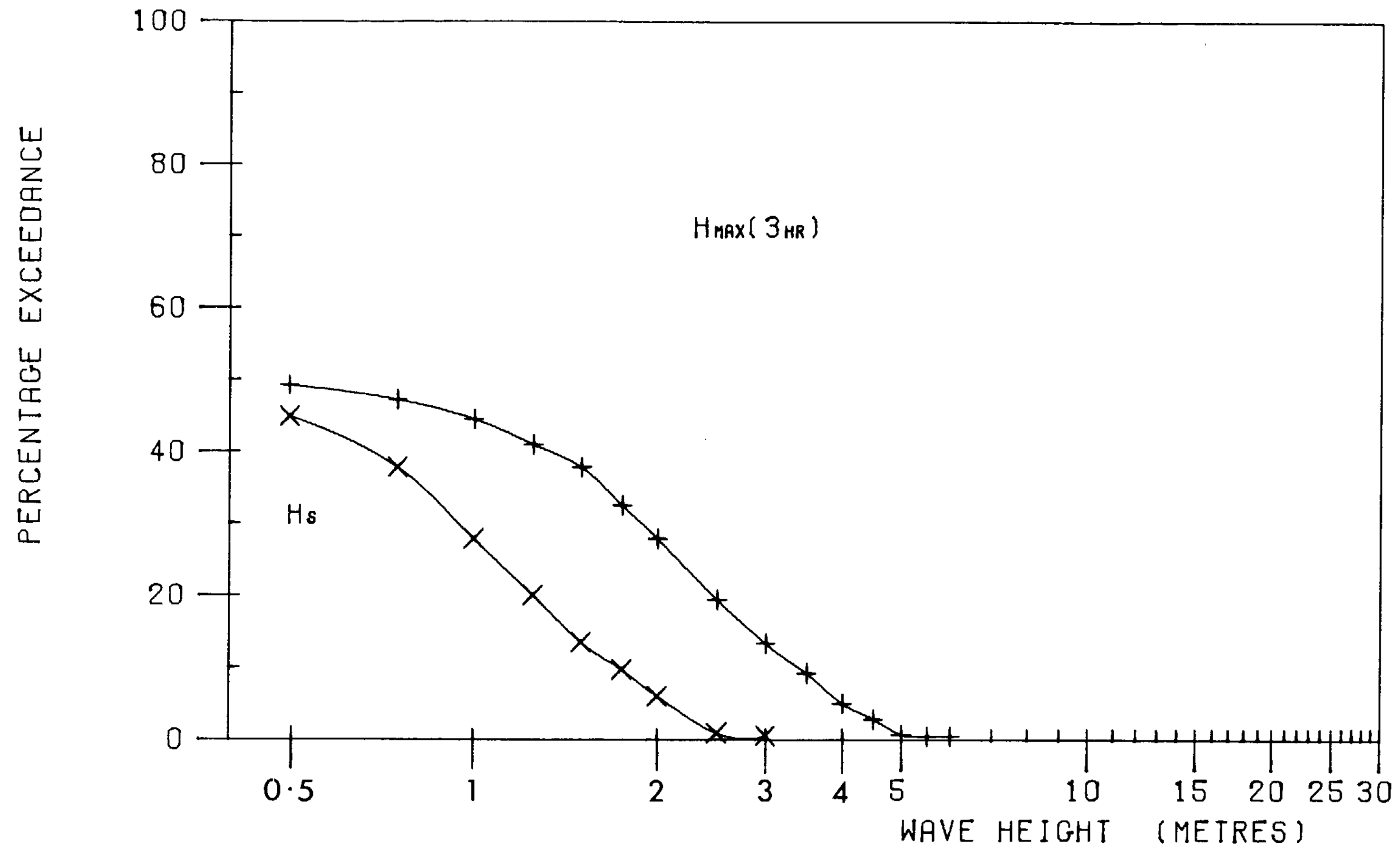


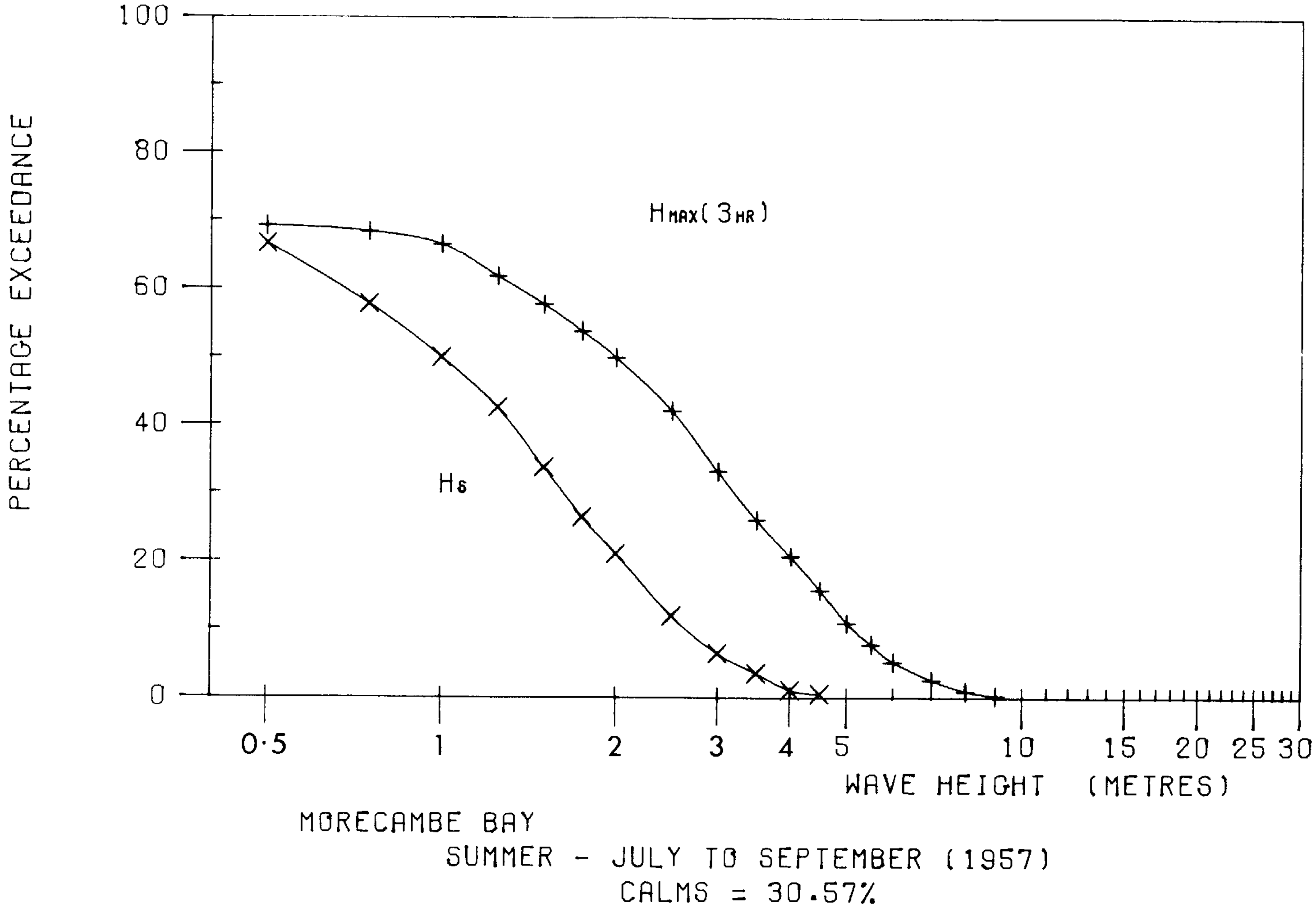
PERCENTAGE EXCEEDANCE
100
80
60
40
20
0
HMAX(3HR)
Hs
0·5
1
2
3
4
5
10
15
20
25
30
WAVE HEIGHT (METRES)
MORECAMBE BAY
WINTER - JANUARY TO MARCH (1957)
CALMS = 19.44%

FIG. 1



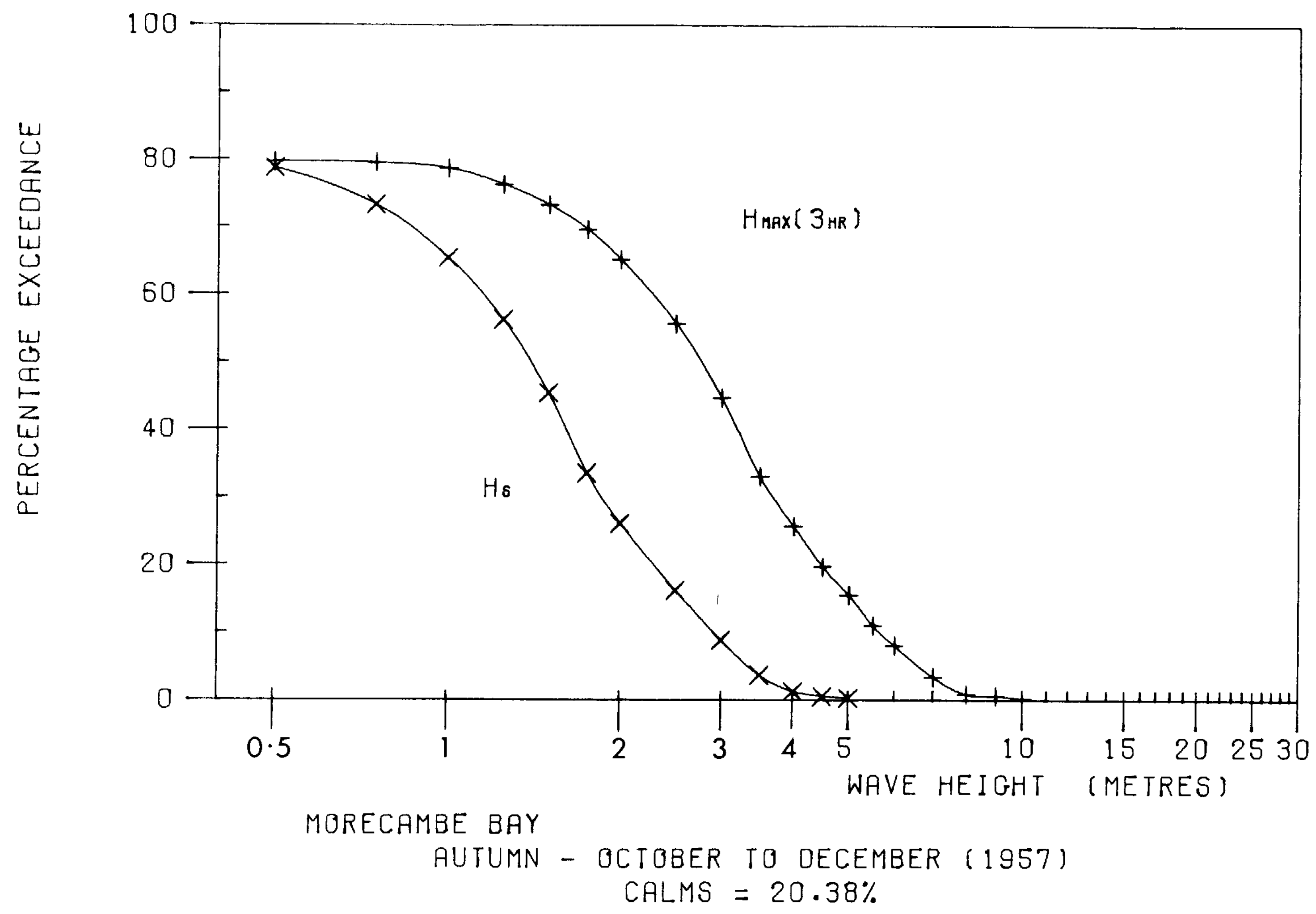
MORECAMBE BAY
SPRING - APRIL TO JUNE (1957)
CALMS = 41.48%

FIG. 2



PERCENTAGE EXCEEDANCE
100
80
60
40
20
0
HMAX(3HR)
Hs
0·5
1
2
3
4
5
10
15
20
25
30
WAVE HEIGHT (METRES)
MORECAMBE BAY
SUMMER - JULY TO SEPTEMBER (1957)
CALMS = 30.57%

FIG. 3


PERCENTAGE EXCEEDANCE
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80
60
40
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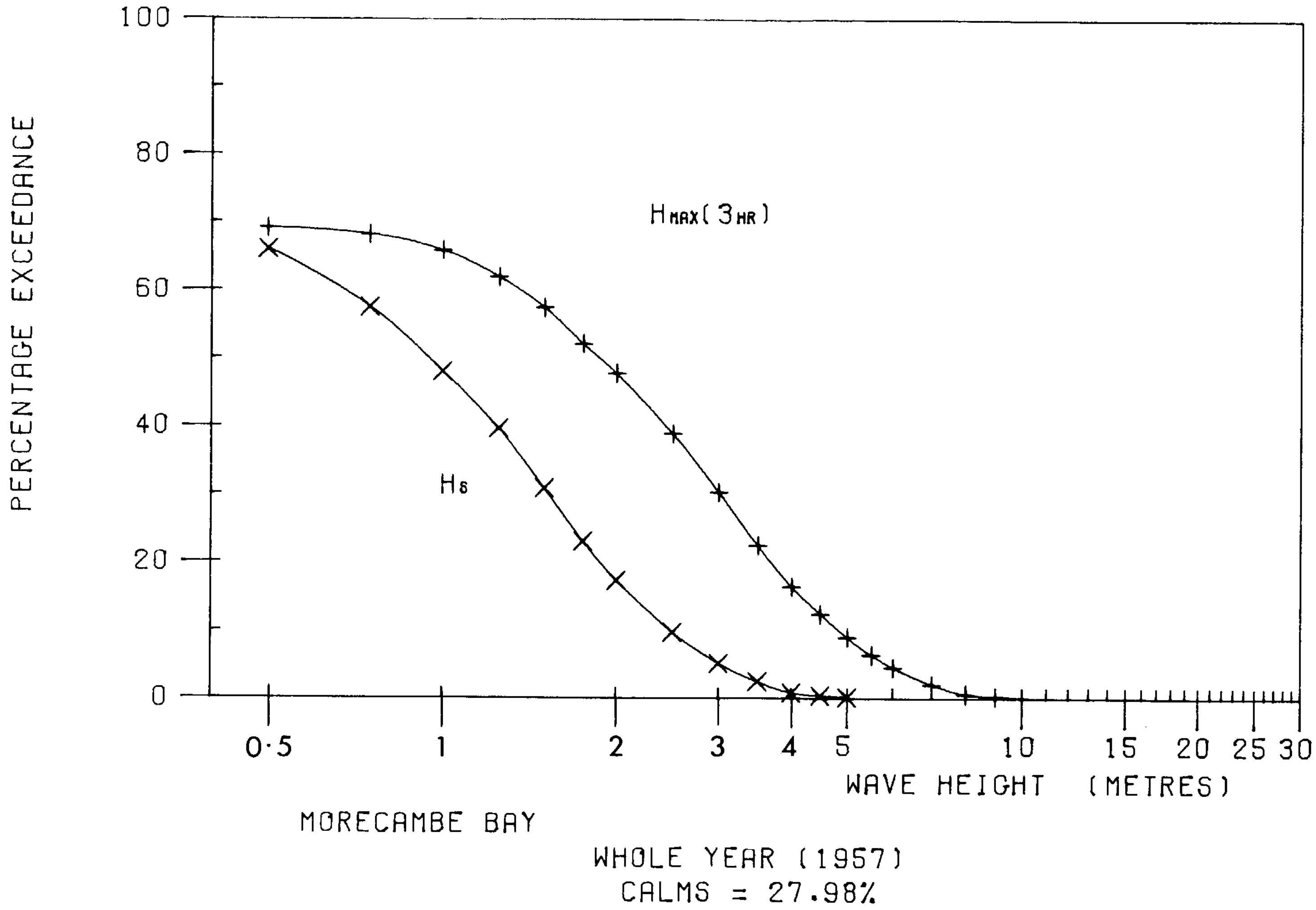
0
0·5
1
2
3
4
5
10
15
20
25
30
WAVE HEIGHT (METRES)
HMAX(3HR)
HS
MORECAMBE BAY
AUTUMN - OCTOBER TO DECEMBER (1957)
CALMS = 20.38%

FIG. 4



100
80
60
40
20
0
PERCENTAGE EXCEEDANCE
HMAX(3HR)
HS
0·5
1
2
3
4
5
10
15
20
25
30
WAVE HEIGHT (METRES)
MORECAMBE BAY
WHOLE YEAR (1957)
CALMS = 27.98%

FIG. 5

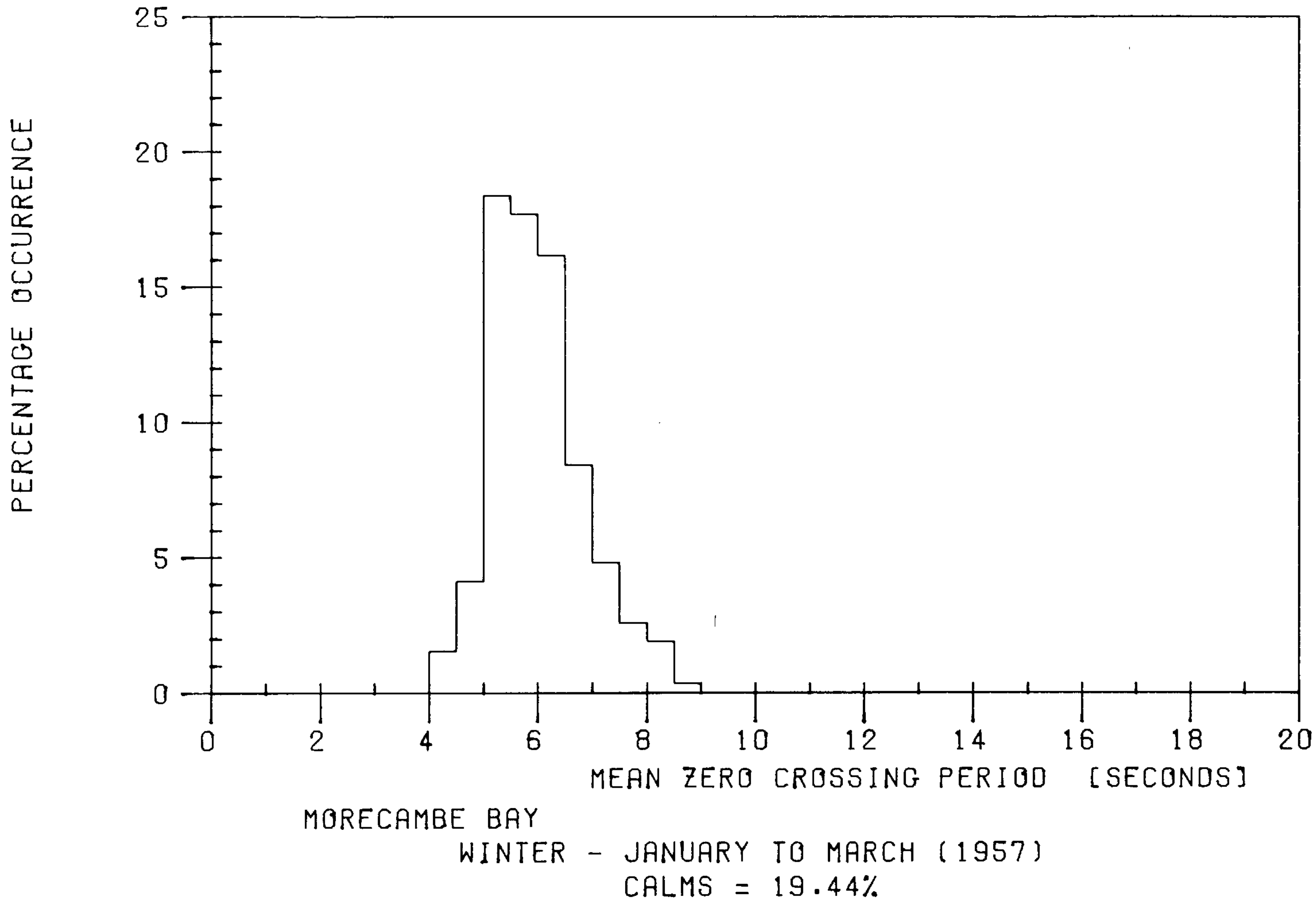
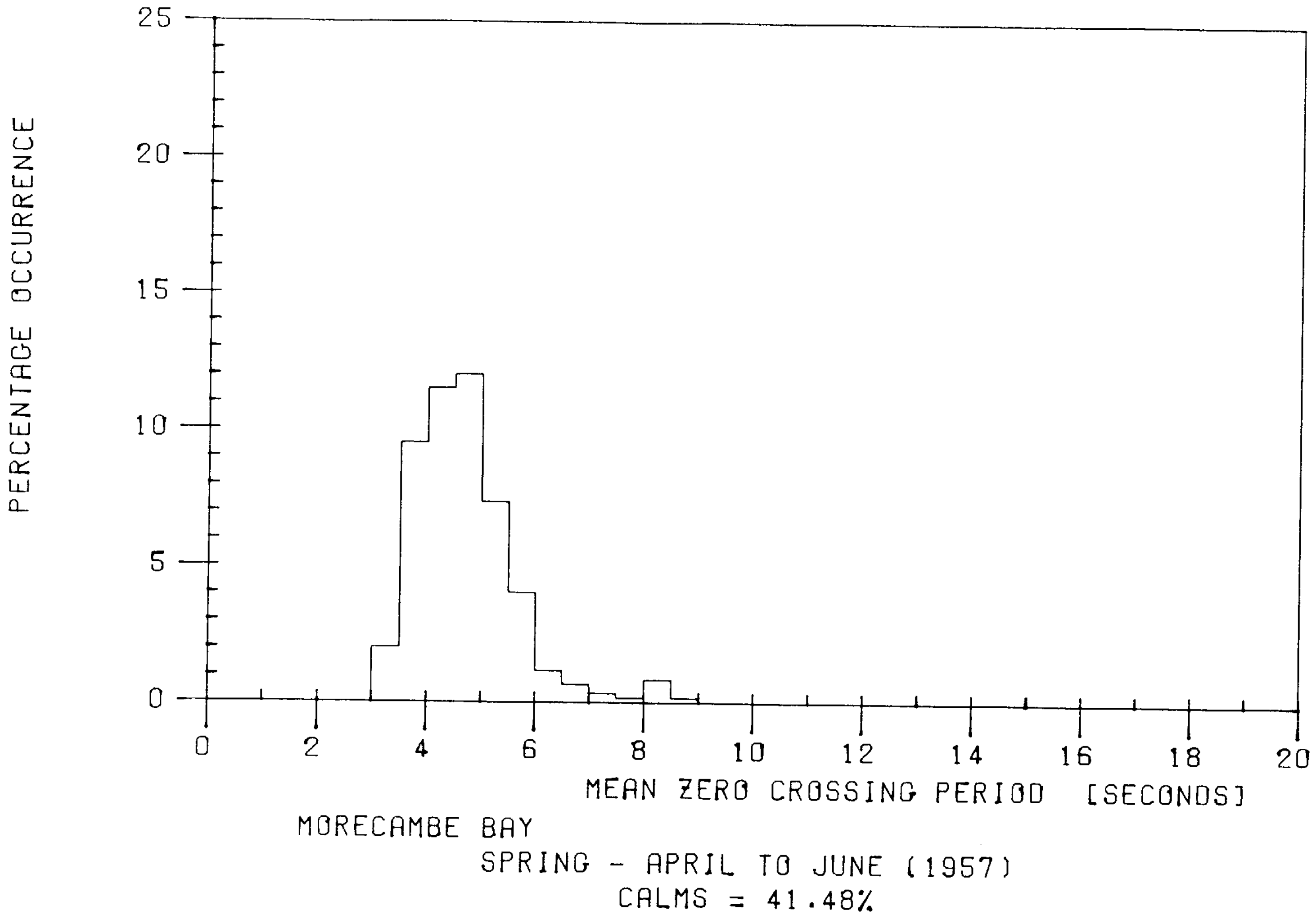

PERCENTAGE OCCURRENCE
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
MORECAMBE BAY
WINTER - JANUARY TO MARCH (1957)
CALMS = 19.44%

FIG. 6



PERCENTAGE OCCURRENCE
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
MORECAMBE BAY
SPRING - APRIL TO JUNE (1957)
CALMS = 41.48%

FIG. 7

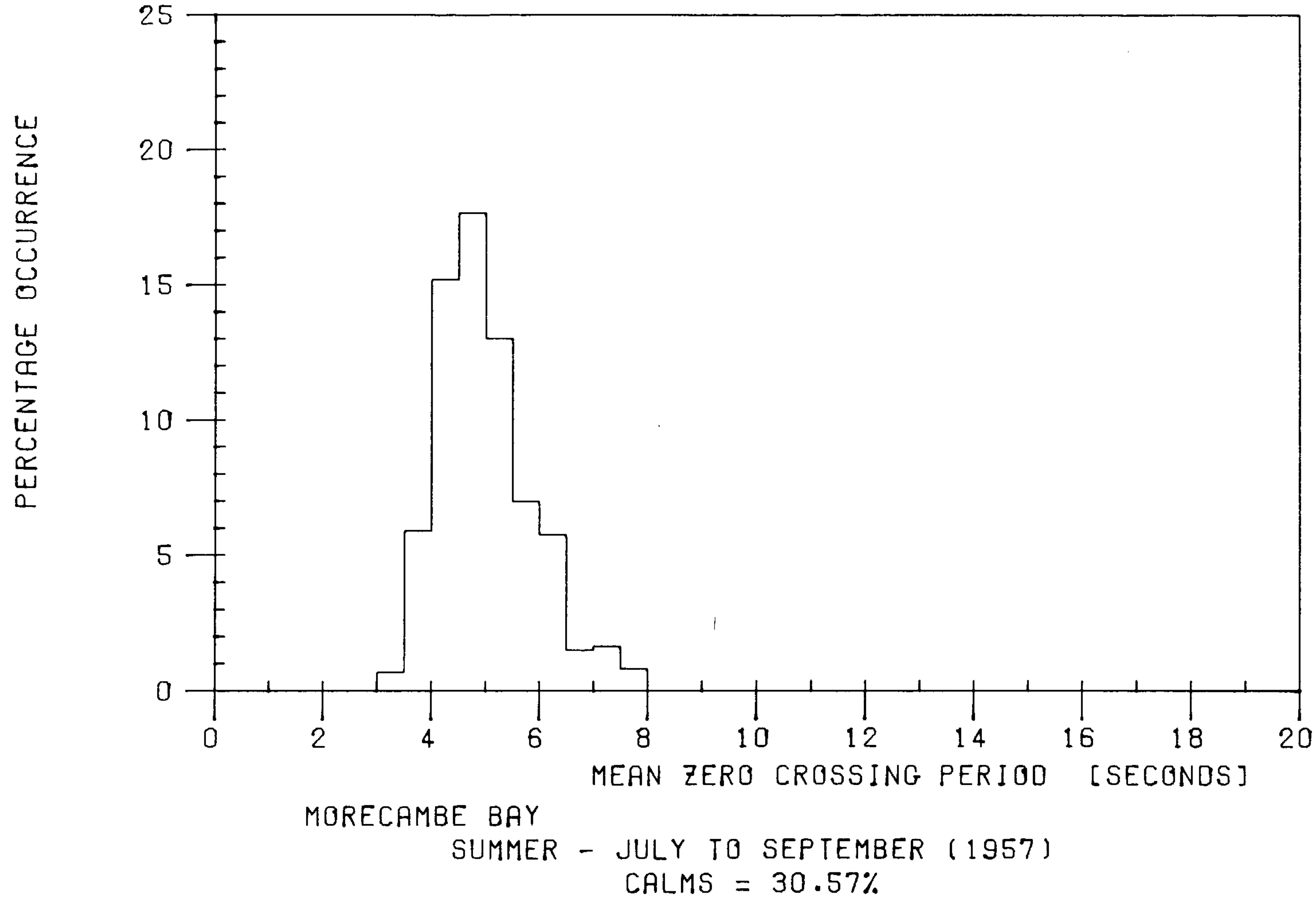
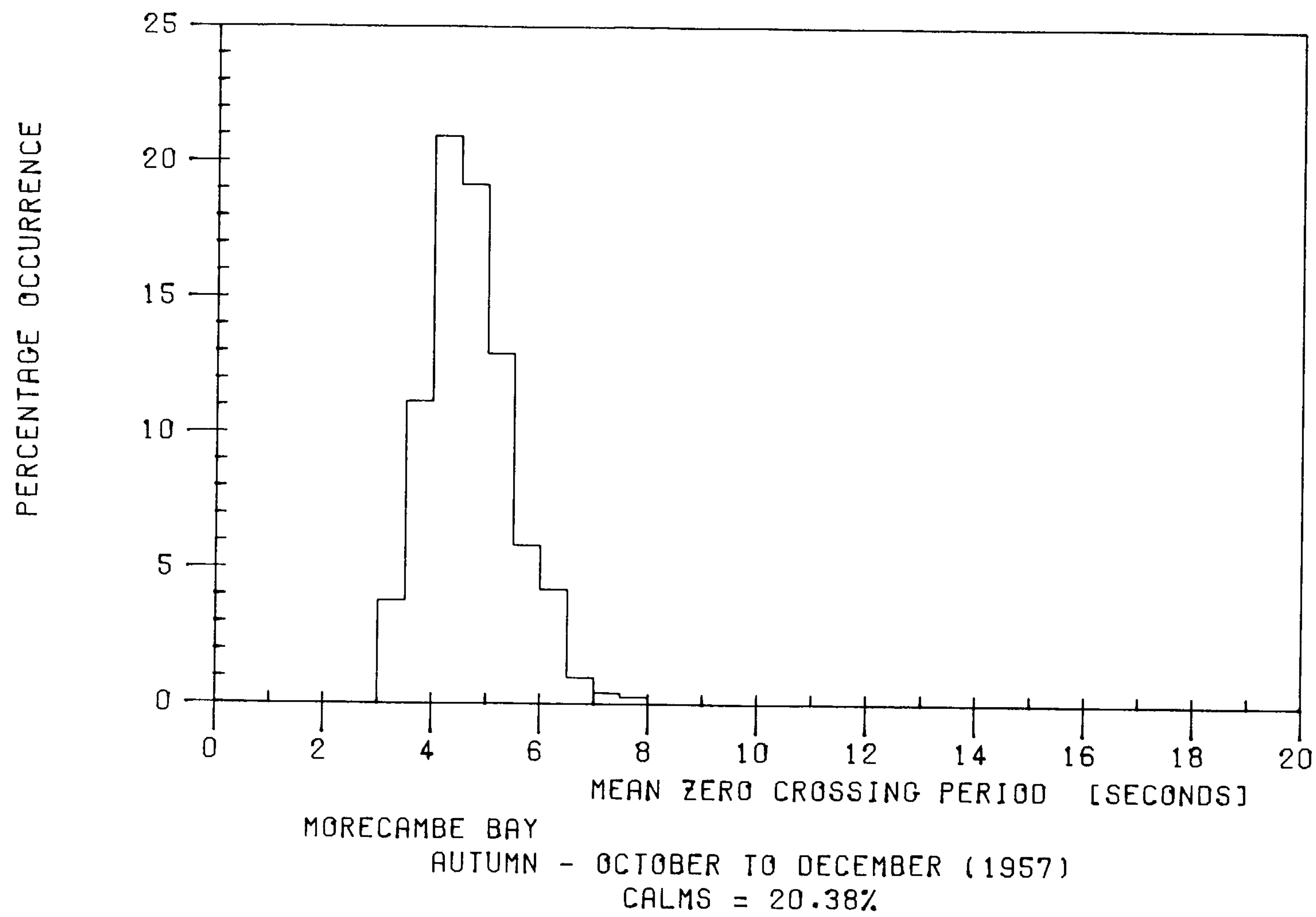

PERCENTAGE OCCURRENCE
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
MORECAMBE BAY
SUMMER - JULY TO SEPTEMBER (1957)
CALMS = 30.57%

FIG. 8


PERCENTAGE OCCURRENCE
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20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
MORECAMBE BAY
AUTUMN - OCTOBER TO DECEMBER (1957)
CALMS = 20.38%

FIG. 9

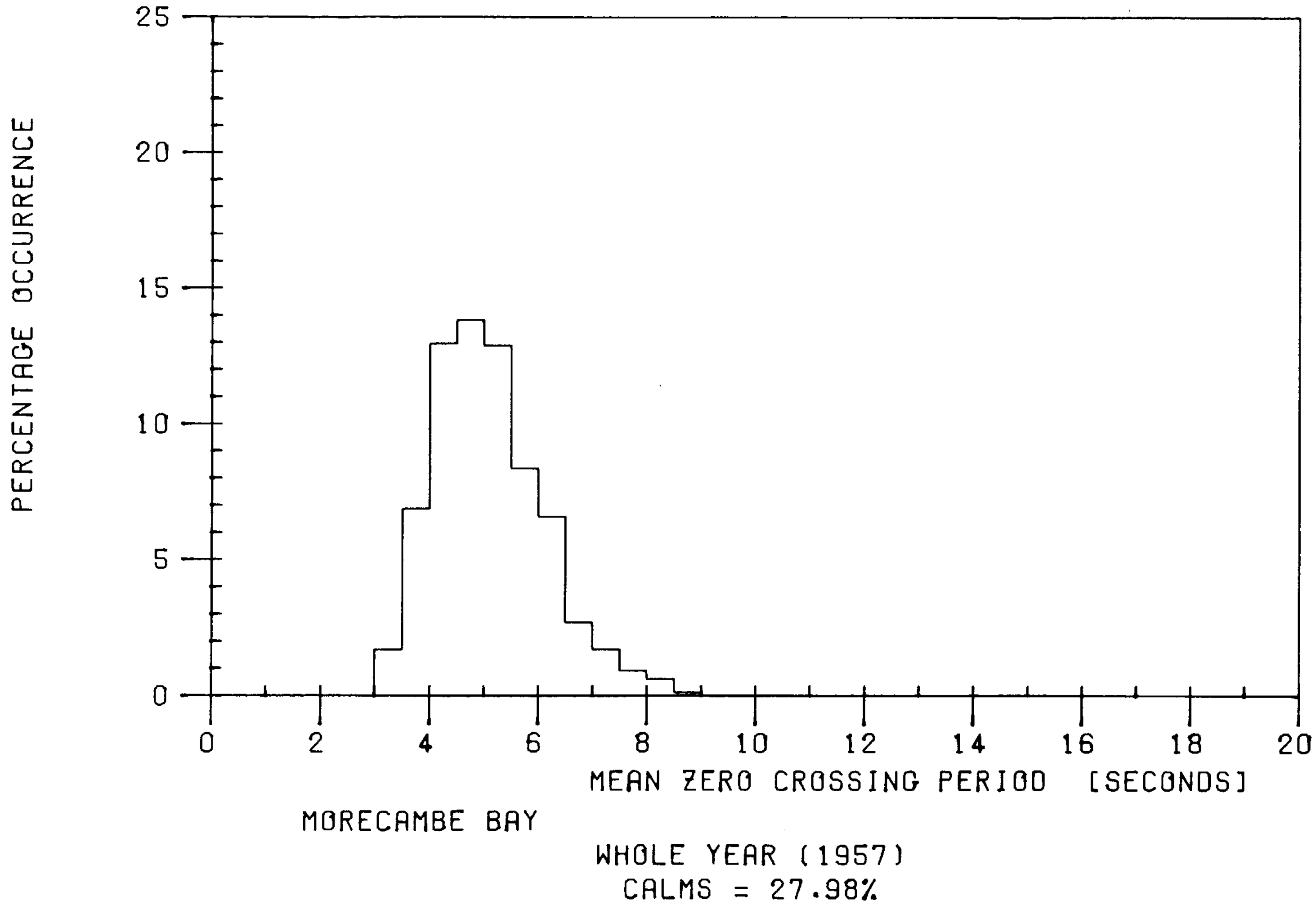

PERCENTAGE OCCURRENCE
25
20
15
10
5
0
0 2 4 6 8 10 12 14 16 18 20
MEAN ZERO CROSSING PERIOD [SECONDS]
MORECAMBE BAY
WHOLE YEAR (1957)
CALMS = 27.98%

FIG. 10

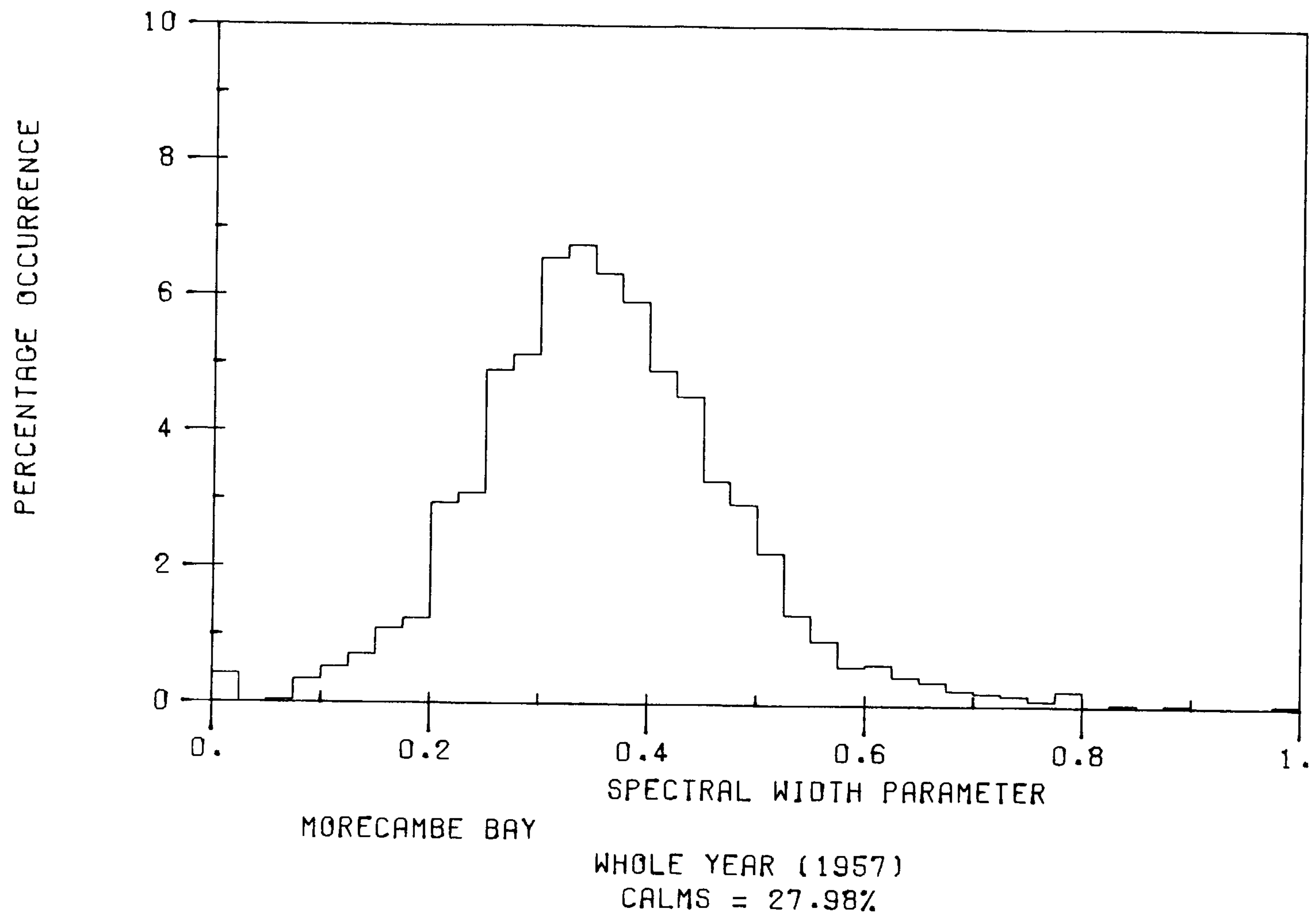
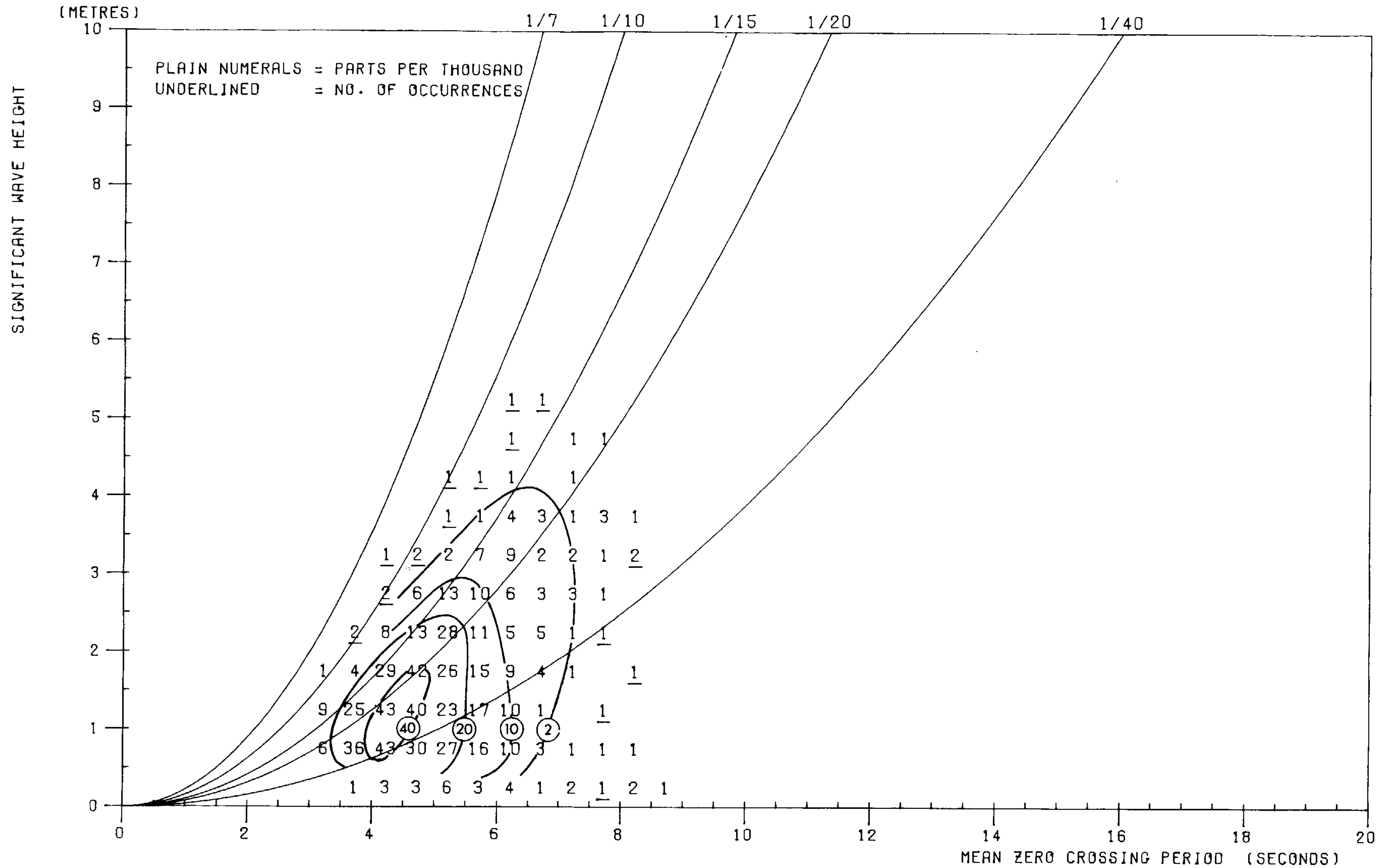

10
8
6
4
2
0
PERCENTAGE OCCURRENCE
0.
0.2
0.4
0.6
0.8
1.
SPECTRAL WIDTH PARAMETER
MORECAMBE BAY
WHOLE YEAR (1957)
CALMS = 27.98%

FIG. 11



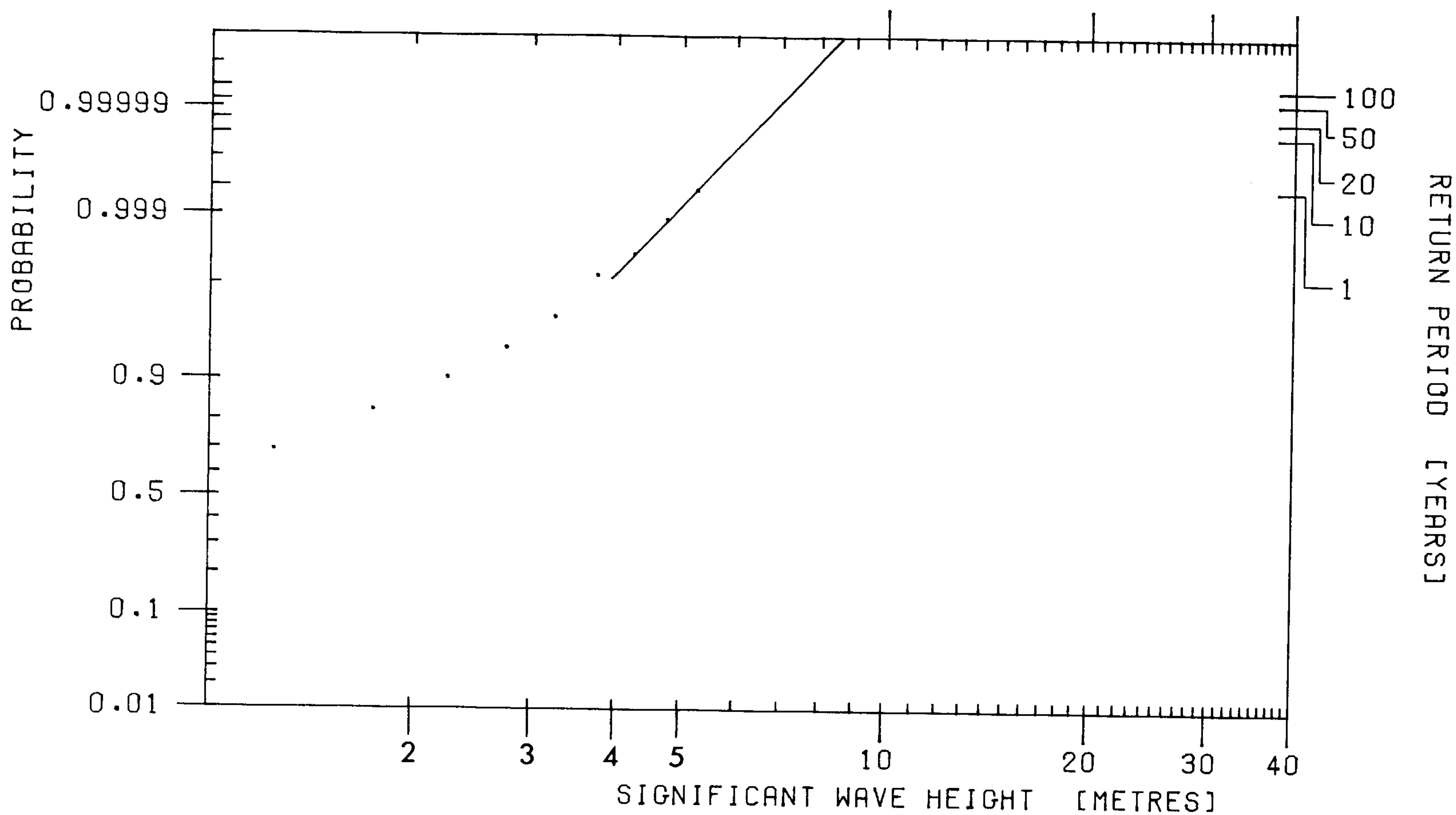
MORECAMBE BAY

WHOLE YEAR (1957)

NUMBER OF RECORDS = 2648

CALMS = 27.98%

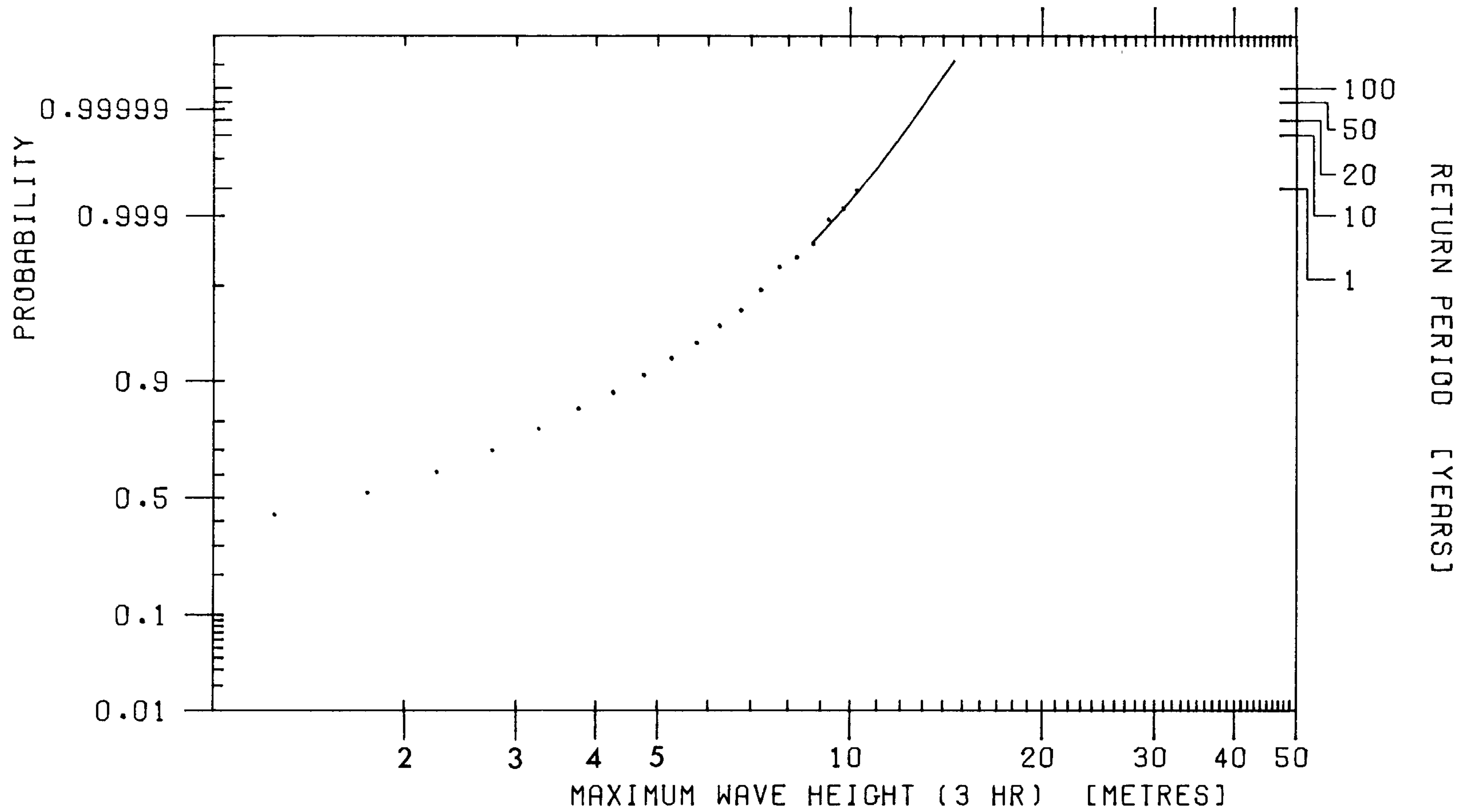
FIG. 12



MORECAMBE BAY

WHOLE YEAR (1957)
CALMS =27.98%
CUMULATIVE PROBABILITY PLOT - LOG-NORMAL SCALE

FIG. 13



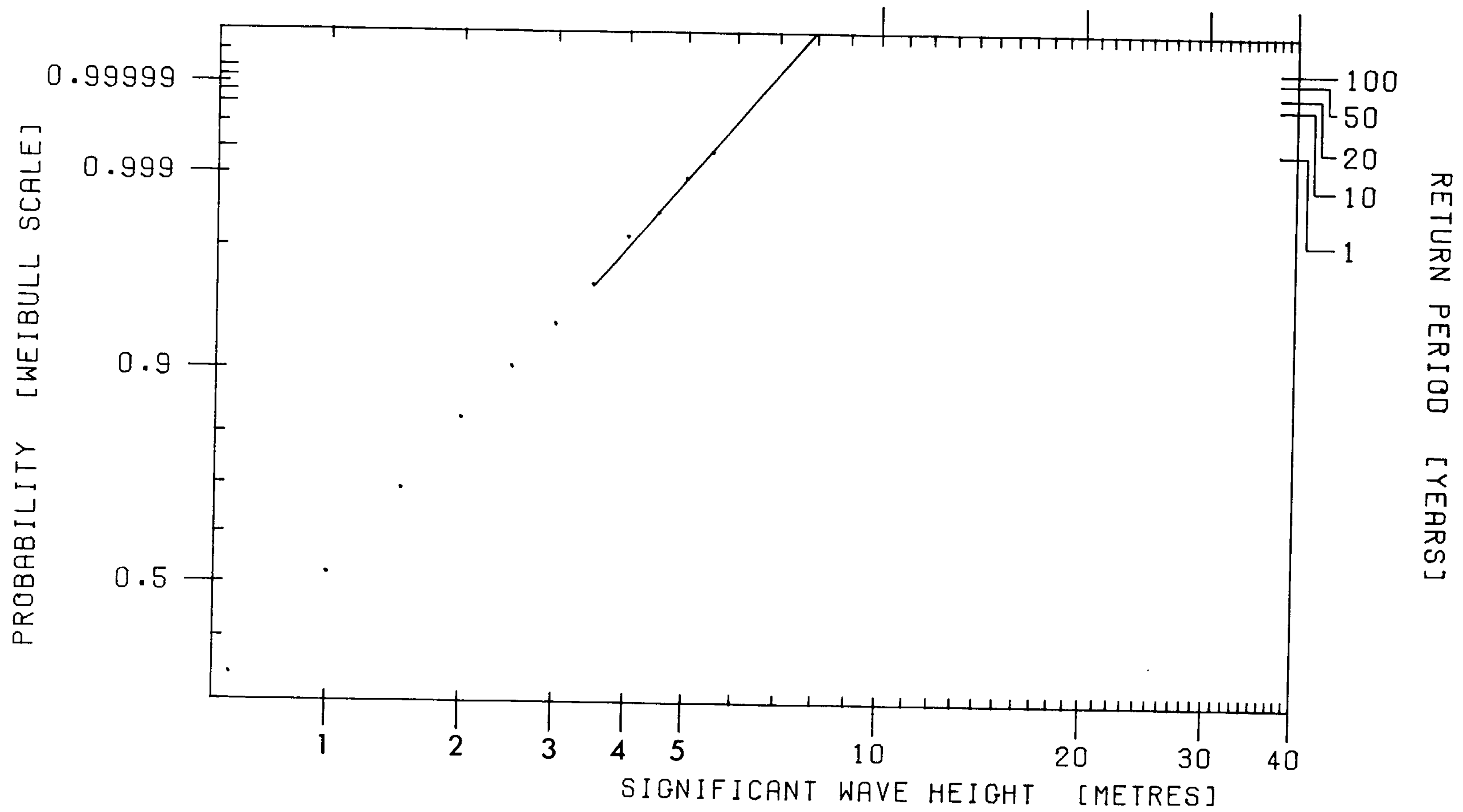
MORECAMBE BAY

WHOLE YEAR (1957)

CALMS =27.98%

CUMULATIVE PROBABILITY PLOT - LOG-NORMAL SCALE

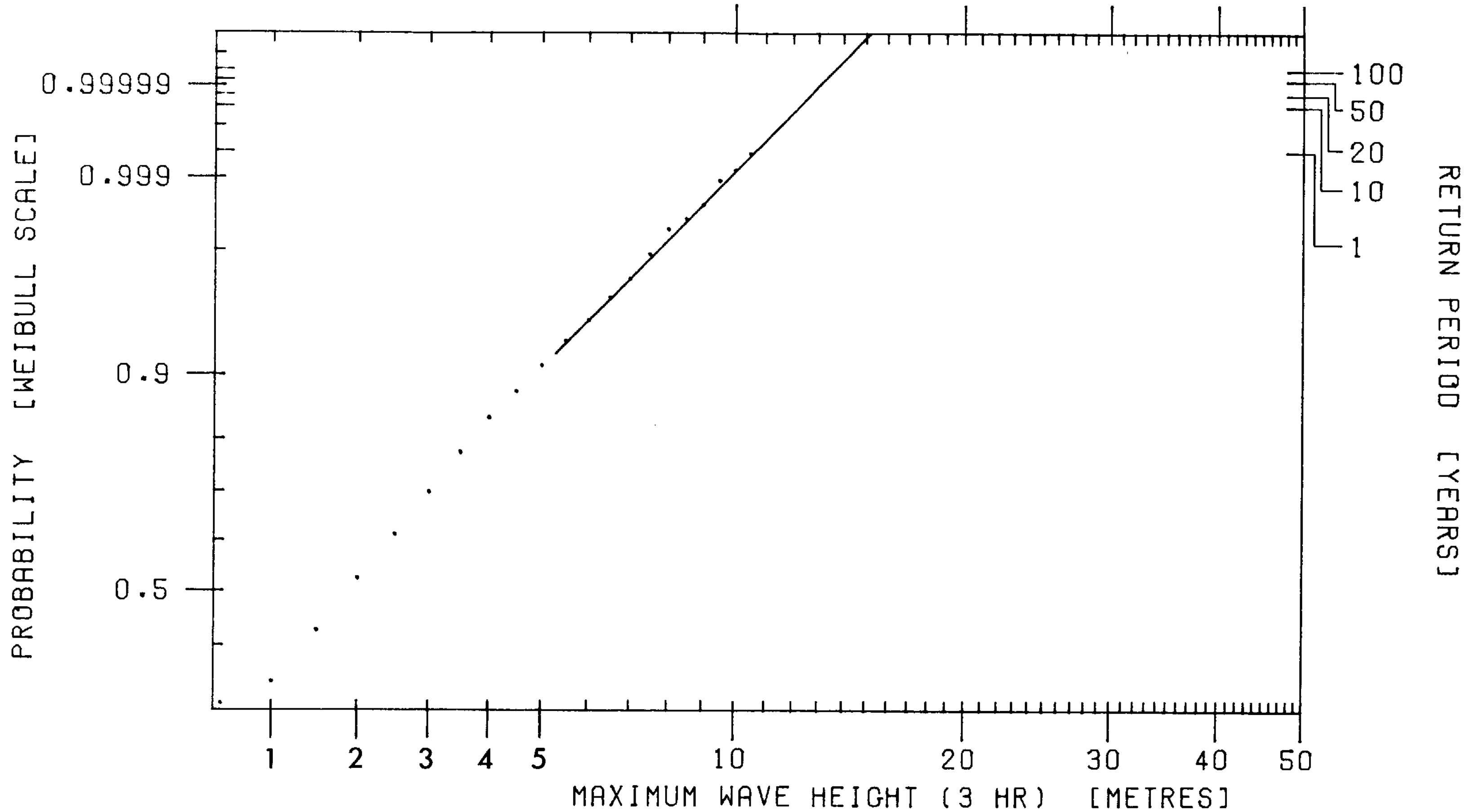
FIG. 14



MORECAMBE BAY

WHOLE YEAR (1957)
CALMS =27.98%
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = -0.9

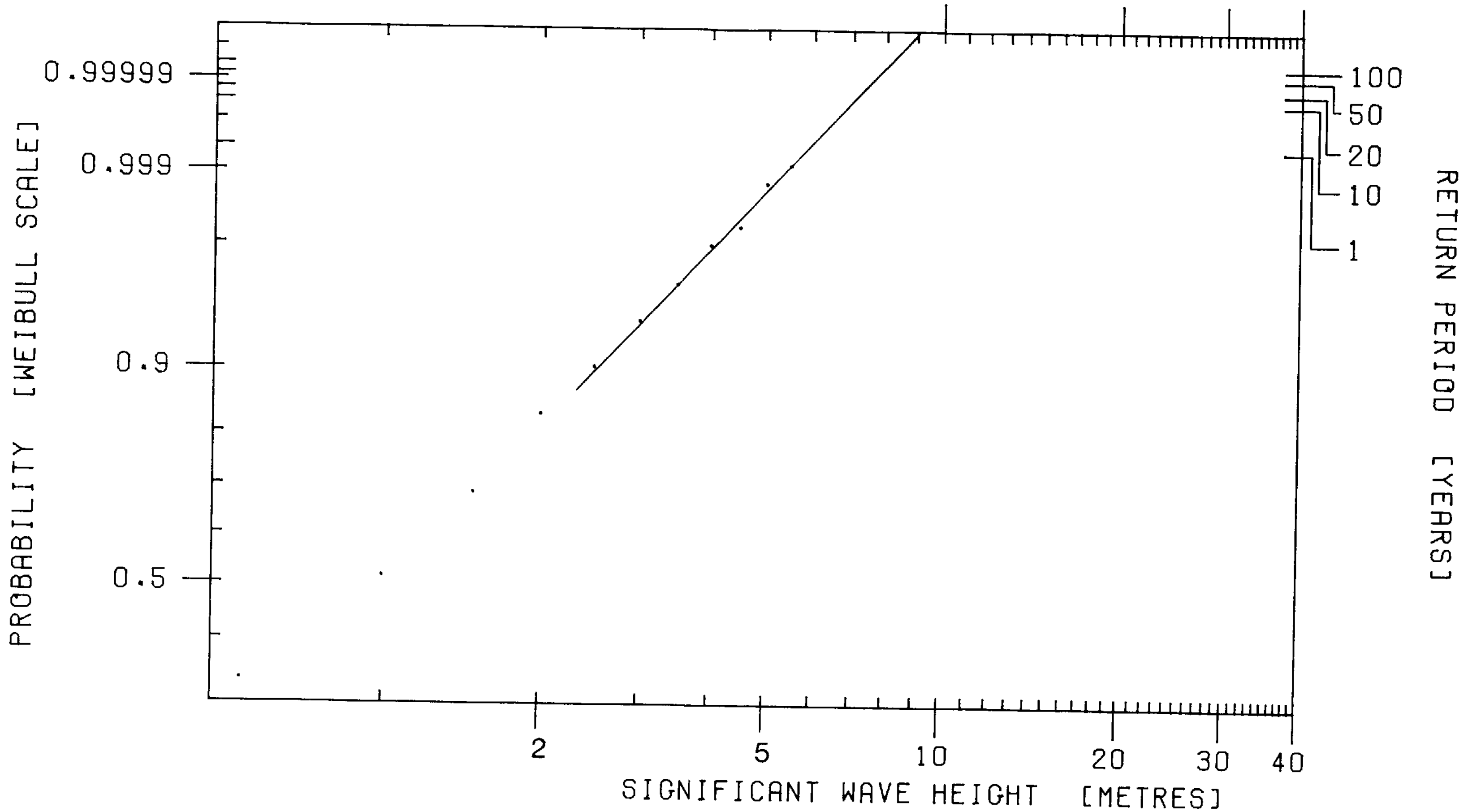
FIG. 15



MORECAMBE BAY

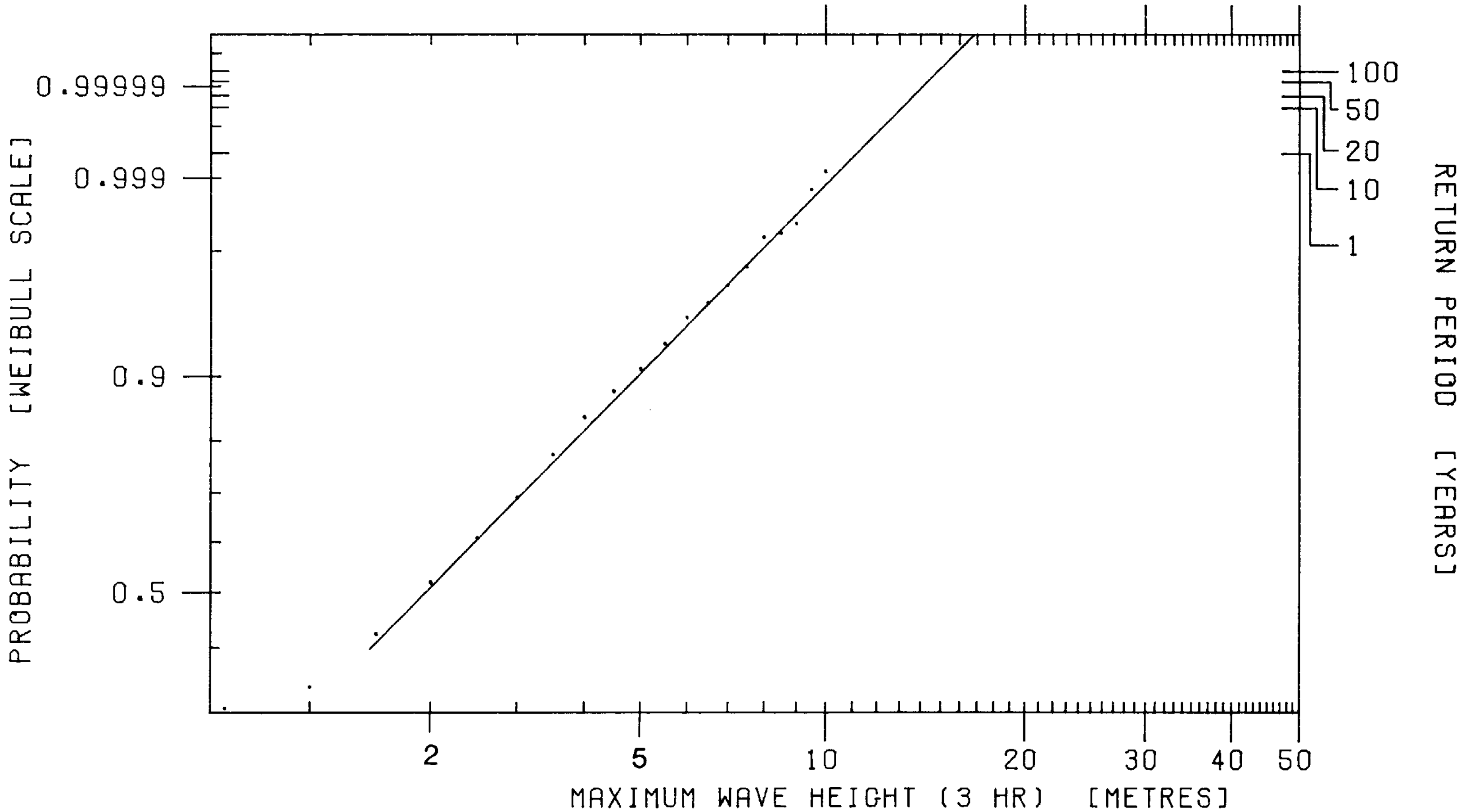
WHOLE YEAR (1957)
CALMS =27.98%
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = -3.3

FIG. 16



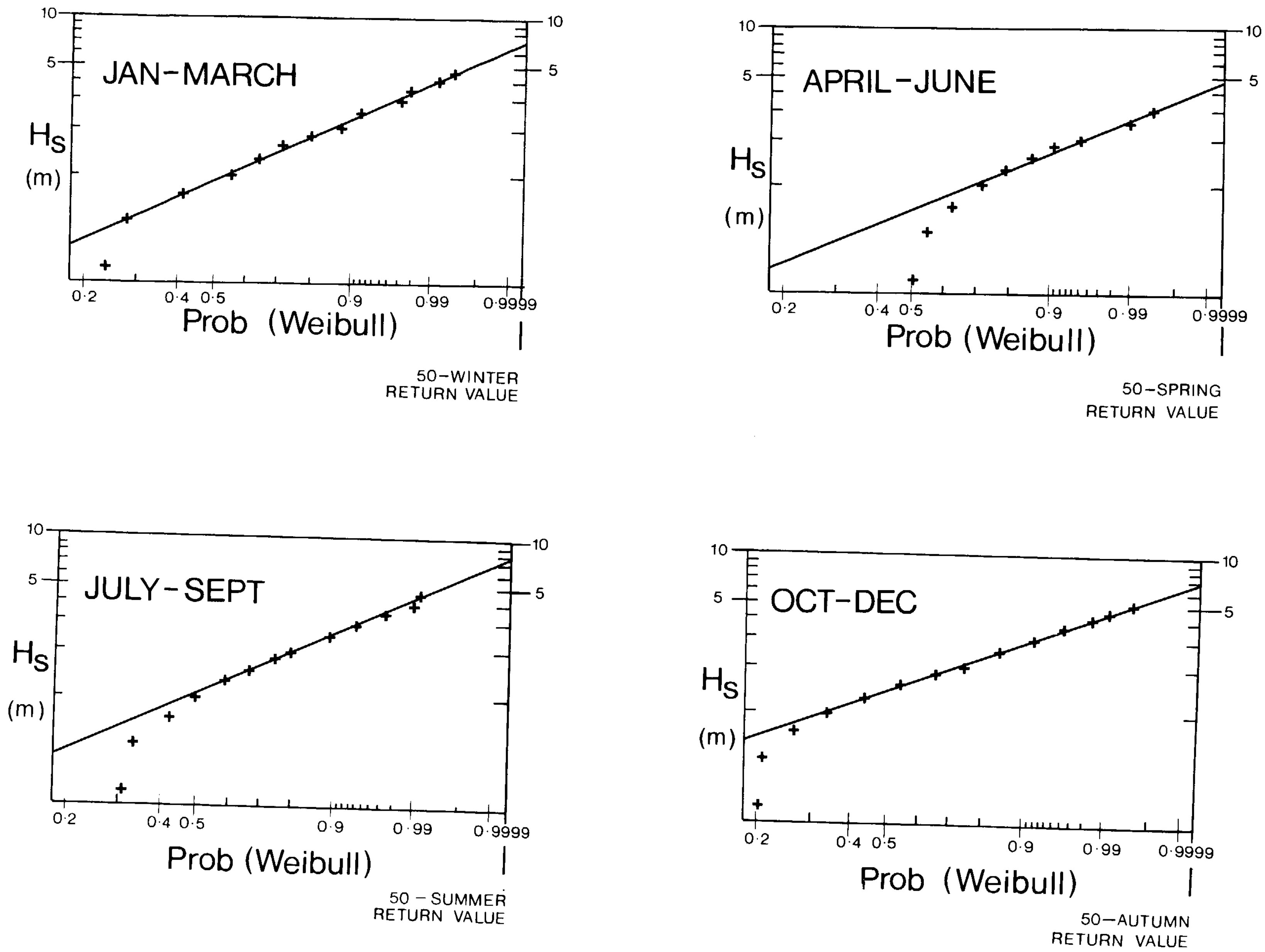
MORECAMBE BAY
WHOLE YEAR (1957) [4 RECORDS/DAY ONLY]
CALMS =27.40%
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = -0.2

FIG. 17



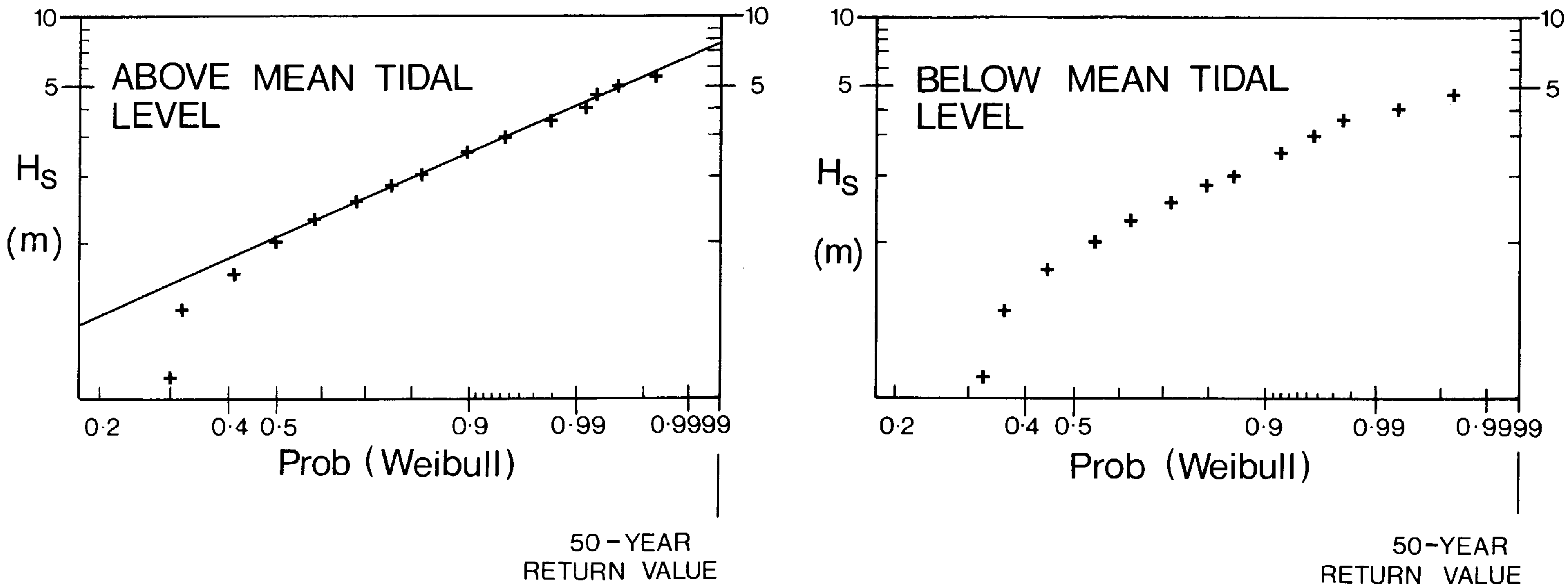
MORECAMBE BAY
WHOLE YEAR (1957) [4 RECORDS/DAY ONLY]
CALMS =27.40%
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = -1.1

FIG. 18



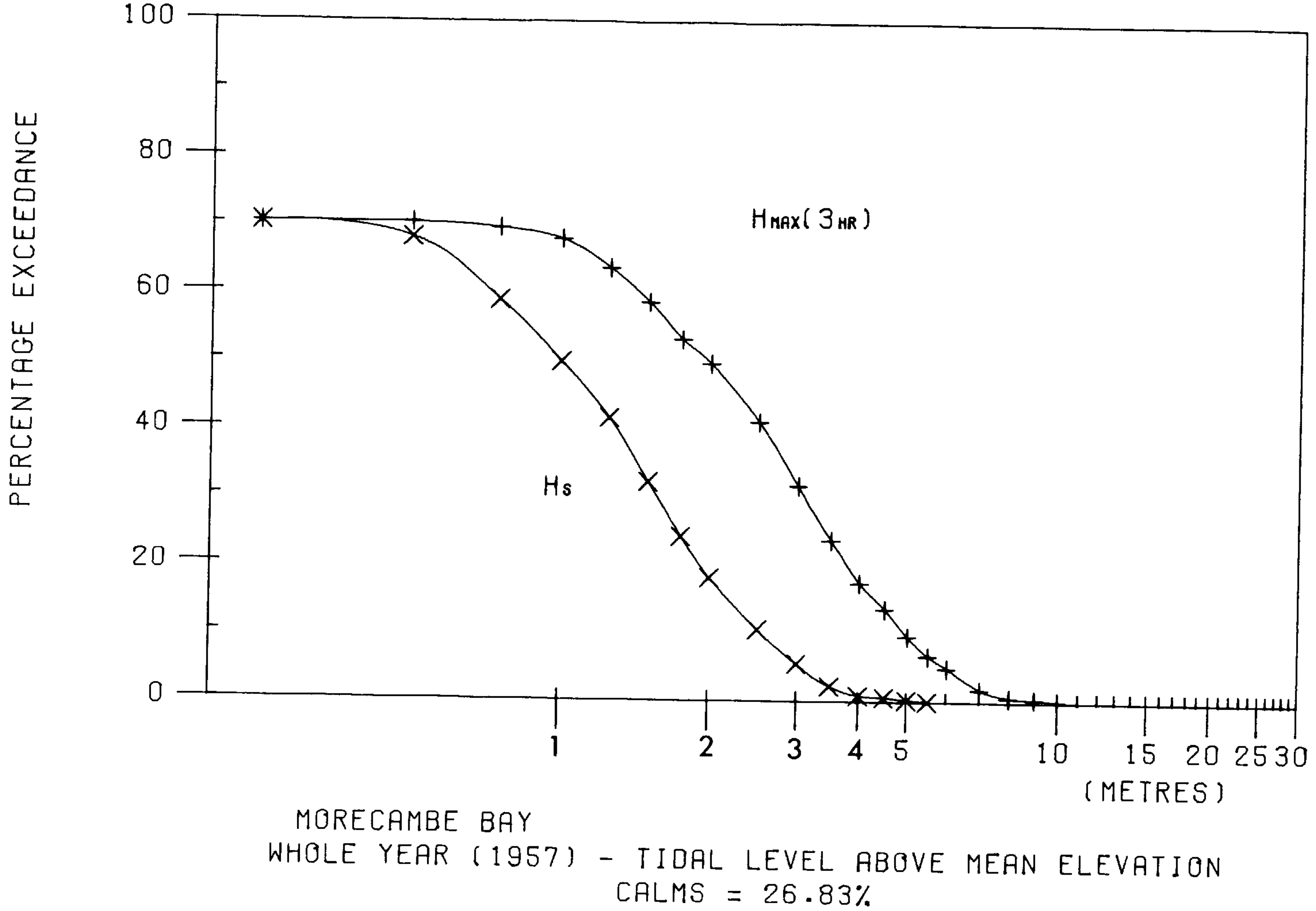
MORECAMBE BAY

FIG.19



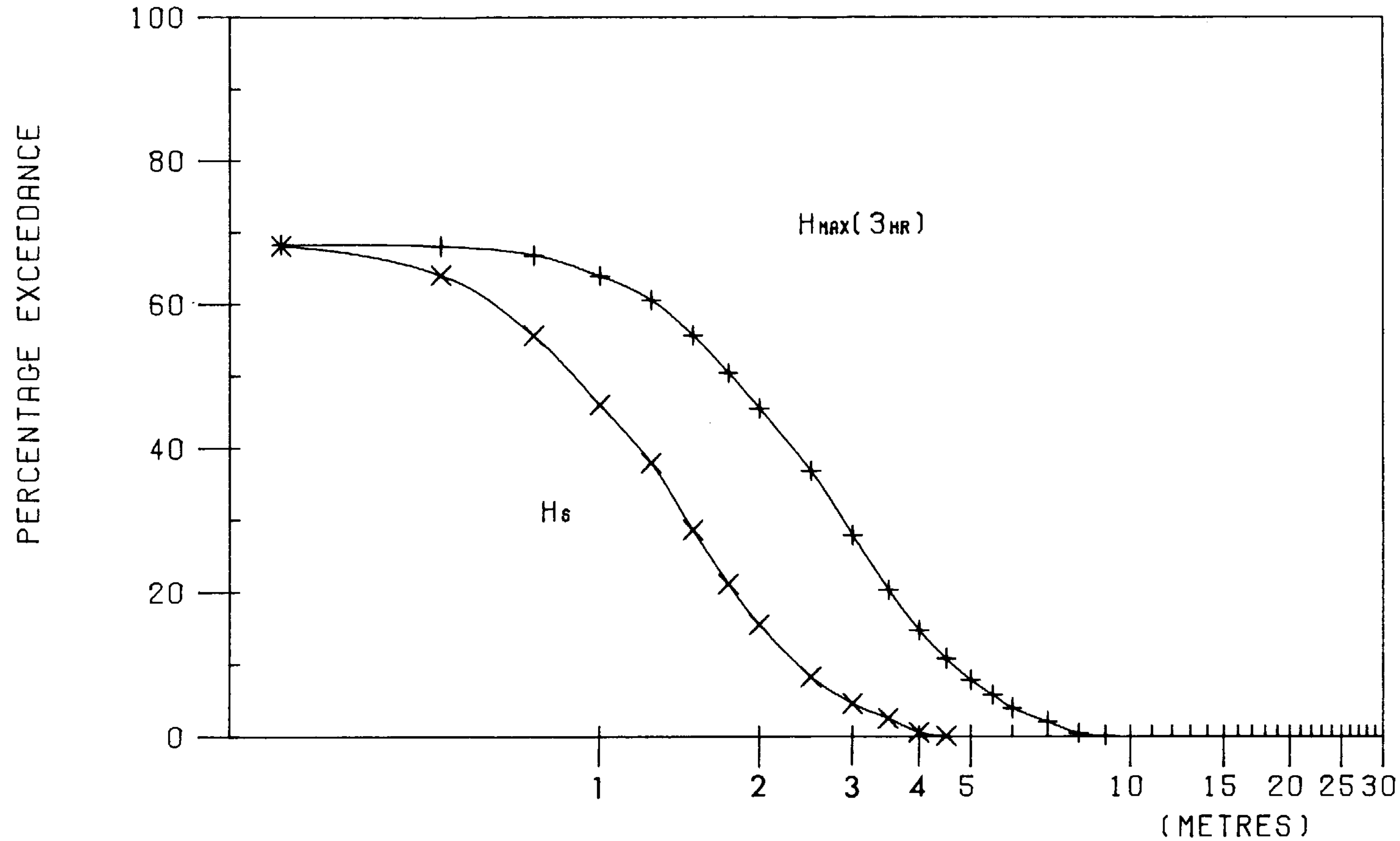
MORECAMBE BAY

FIG. 20



PERCENTAGE EXCEEDANCE
100
80
60
40
20
0
HMAX(3HR)
Hs
1
2
3
4
5
10
15
20
25
30
(METRES)
MORECAMBE BAY
WHOLE YEAR (1957) - TIDAL LEVEL ABOVE MEAN ELEVATION
CALMS = 26.83%

FIG. 21



MORECAMBE BAY
WHOLE YEAR (1957) - TIDAL LEVEL BELOW MEAN ELEVATION
CALMS = 28.43%

FIG. 22