I.O.S.

WAVE MEASUREMENTS AT NORTH ATLANTIC WEATHER STATIONS INDIA AND JULIETT IN THE NINETEEN SEVENTIES (INDIA 2 AND JULIETT 2)

BY

L. DRAPER

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NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE OF OCEANOGRAPHIC SCIENCES

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WORMLEY

Wave measurements at North Atlantic Weather Stations INDIA and JULIETT in the nineteen seventies (INDIA 2 and JULIETT 2)

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OCEAN WEATHER SHIP STATIONS

MIKE	66°N	02°E
INDIA	59°N	19°W
LIMA	57°N	20°W
JULIETT	52°30'N	20°W
KILO	45°N	16°W

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ABSTRACT

Measurements of surface waves have been made intermittently from 1953 to 1975 at Ocean Weather Stations INDIA (59°N 19°W) and JULIETT (52°30'N 20°W) using Shipborne Wave Recorders. Measurements made during the first decade of the project were analysed, and published in the late sixties. Measurements made in the second decade have been analysed and the results are published in this report; they may be taken as representative of wave conditions existing over a typical year, divided into the four seasons. Estimates of extreme heights having various return periods are also made.

There are significant increases in wave heights deduced from these analyses compared with those in the previous studies; they were more severe in the early seventies than in the early sixties. All conceivable sources of error have been investigated to try to understand the reasons for the differences but none of any significance has been found.

It therefore seems necessary to accept that wave conditions can be more severe than had previously been believed.

INTRODUCTION

Background to surface wave measurements at Ocean Weather Stations

Measurements started in 1953, using a Shipborne Wave Recorder (Tucker, 1956) mounted on OWS WEATHER EXPLORER (formerly a Flower Class Corvette), one of the four British vessels in service at that time. They occupied four stations, ALPHA, INDIA, JULIETT and KILO in rotation with Dutch and French ships. Because of this sparse occupation level by a wave-recorder-carrying vessel, it was not possible to obtain a continuum of records. Indeed, it took many years before the ships had been on station long enough to accumulate sufficient records to produce an acceptable number, for every calendar month, from any one station, to allow wave climate data to be published; this stipulation was made to allow a uniform representation throughout the year. The situation is exacerbated by the fact that the recorded wave period is apparently altered by an incalculable amount when the vessel itself moves relative to the water. If the sea waves were all to come from one known direction and the speed and direction of the vessel were known, there would be no problem, but when wave energy comes from a range of directions, as is always the case, and the vessel has to move to keep station, the apparent period, and to a lesser extent the height, is irretrievably modified. The acceptable criteria in these analyses were that the vessels were within about 20 nm of their nominal positions and that the station-keeping speed was 2 knots or less; this latter one makes only a 10% modification to the lowest period waves, about 4 sec, considered, and proportionately less to longer period waves. In addition, electronic devices have been known to fail or lose their calibrations, and when any doubt at all existed, a recording was deemed to be unuseable for this purpose. The mean depths at INDIA were 2000 m and at JULIETT were 3000 m.

In May 1958, WEATHER EXPLORER was retired and the instrument transferred to WEATHER REPORTER (formerly a Castle Class Corvette). By 1964 there were enough records available to permit an analysis of 1440 records from JULIETT (now referred to as JULIETT 1) on location 52°30'N 20°W, and 2400 records from INDIA (now referred to as INDIA 1) on location 59°N 19°W. The results of these analyses were published in two papers (Draper and Whitaker, 1965; Draper and Squire, 1967). They suggested that the wave climates at the two locations were indistinguishable. These two reports, and especially the INDIA one, have become the base references on which many engineering projects have been planned. In particular, INDIA data have been the main components of environmental input to the design of wave energy devices for use in severe conditions.

In November 1966, a second instrument was deployed on WEATHER ADVISER, a sister ship to WEATHER REPORTER. Because there were then two ships in service it took less time to find enough records to assemble a composite 'year' of wave records correctly distributed throughout the calendar months. The analysis was undertaken starting from the more recent dates and working back in time to fill gaps in the sequence. For INDIA and JULIETT, these records have now been analysed and are referred to as INDIA 2 and JULIETT 2.

In mid 1975 ALPHA, INDIA and JULIETT were abandoned, the latter two being replaced by station LIMA on location 57°N 20°W, between their old locations. From this time there was always a wave recorder on station giving a continuous sequence of records, interrupted only by the ship steaming and by electronic faults.

Most of the records for both stations were taken in 1975, 1974 and 1973, with a few from 1971 and 1970. At that time the Shipborne Wave Recorder was calibrated to give wave height in feet, so this measurement unit was used for analysis of individual wave recorder traces, but before presentation the data were converted to metres.

ANALYSIS OF WAVE RECORDS

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 explained 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 (these do not need to be consecutive).

H_2 = The sum of the distances from the mean water level of the second highest crest and the second lowest trough (these do not need to be consecutive).

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 (1.9 m) for WEATHER ADVISER and 7.1 ft (2.2 m) for WEATHER REPORTER. These are the mean depths for each vessel; on each voyage the depths were greater on departure and less on return because of the consumption of fuel and water.

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

H_s = The significant wave height (defined as 4 sigma, where sigma is the root mean square surface elevation).

$H_{max(3\ hours)}$ = The most probable value of the height of the highest zero-up-crossing wave during a three-hour interval (Draper, 1963).

RESULTS OF THE MEASUREMENT PROGRAMME

INDIA 2

(a) The most severe wave conditions

The highest value of H_1 in this analysis, actual wave height after correction for instrumental response, measured at OWS INDIA was 26.3m (significant height 15.7m) with a mean zero-crossing period T_z of 12.9sec, at 00hr 30.12.72, although there were two other records with higher values of significant wave height. Not only was it an extreme value of H_1, but it was a real wave with the crest and trough being consecutive. This 26.3m wave is the highest which we, or to our knowledge anyone else, has ever measured with an instrument. Also, the depth of the trough was about one metre greater than was the height of the crest, conflicting with the common concept of huge waves being largely composed of disproportionately high crests, but giving credibility to stories of 'holes in the ocean' (Byles, 1965). This is a relatively unusual wave because with such a value of significant wave height (see Table I, third line down) in a fairly broad-band sea, only one individual wave in about 1400 can be expected to be above that height, assuming a Rayleigh distribution; this is equivalent to a duration of about 5 hours. The second-highest wave in the measurements had a value of H_1 of 23.0m springing from the fifth-highest significant wave height, of 13.6m, and with a mean zero-crossing period of 11.5sec, at 09hr on the same day as the highest wave.

Values of significant wave height and the most probable value of the height of the highest wave in 3 hours (the recording interval) are normally derived statistically from the two measurements H_1 and H_2 (first and second highest waves) taken from the short analogue record. In general, errors caused by the statistical variations inherent in the short sample and the necessarily-rapid analytical techniques can be expected to cancel out for the bulk of the data, but for the very highest recorded waves there is a strong possibility that the highest wave on a record was itself the 3-hour (or even longer interval) wave. Accordingly, it is sensible to determine significant wave height by a more comprehensive method. This has been done for each of the five records showing the highest individual values of H_1, calculating the average height of the highest one-third of the crests, using excursions from the mean, and similarly with the average troughs, and then adding the two values to yield a more widely-based estimate of significant wave height. These values have replaced the mass-produced values in the original data set. The interesting, and unexpected, result from this check is that three of the five highest values in the initial analysis underestimated the true value of significant wave height by about one metre; the other two were, as expected, over-estimates. These five most severe (significant height) conditions were as follows:

TABLE I

Records having the five largest values of Significant Wave Height
(Values derived from H_1 and H_2 are given in brackets)

Day No	Date	hr	T_z sec	HEIGHTS (in metres)	
				Significant(H_s)	Highest on Record
364	30.12.72	03	15.4	17.4 (16.4)	22.1
299	26.10.74	21	12.2	15.8 (14.7)	21.8
364	30.12.72	00	12.9	15.7 (17.0)	26.3
364	30.12.72	06	12.3	15.2 (14.1)	20.4
364	30.12.72	09	11.5	13.6 (14.5)	23.0

(b) Calms

There were no calms (defined as significant height of 0.5m or less); on only about ten occasions did the significant height fall below 1 metre, the lowest calculated value being 0.58m.

(c) Seasonal and Annual Distributions

The results of the analysis of all the three-hourly records are shown in the figures, prepared using the IOS forms of presentation recommended for engineering purposes (Draper, 1966). Some of these figures give results for individual seasons defined as follows:

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

Note that in this analysis the leap year is ignored.

Figures 1-4 show the cumulative distributions of H_s and of $H_{max(3\ hours)}$ for each of the four seasons, and Figure 5 gives the distribution for the whole year. For example, Figure 1 shows that during the winter the significant wave height exceeded 5.7 metres for 50% of the time, while Figure 5 shows that a 3.7 metre significant wave height was exceeded for 50% of the entire 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 of T_z was least during the summer, at 7.5-8 seconds, and greatest during the winter, at 9-9.5 seconds. The largest zero-crossing periods were around 15 seconds in the autumn and winter seasons. The histograms show the smallest values of T_z to be about 5 seconds; the rapid attenuation of short waves with depth causes the Shipborne Wave Recorder pressure sensors to be insensitive at periods shorter than this.

Figure 11 is a scatter diagram showing the joint distribution throughout the year of significant wave height and zero-up-crossing period. For example, the most frequently-occurring combinations were waves with significant wave heights of between 2 and 4 metres and periods of between 7.5 and 8.5 seconds. These occurred for 18.4% of the time, or, since there are 2920 three-hour durations (and samples) in an average year, on about 540 occasions.

Wave steepness is defined as the ratio of wave height : wave length; lines of constant significant wave height steepness 1:7, 1:10, 1:15, 1:20 and 1:40 are drawn on Figure 11 (wave length was computed using simple wave theory, i.e. $L=gT^2/2\pi$ where T is deemed to be the zero-crossing wave period T_z).

Figure 12 is a more detailed version of Figure 11 but it excludes the most severe conditions. Note that rounding can cause apparent differences of one in the totals within particular height and period ranges.

(d) Extreme Conditions

i) Wave Heights

Figures 13-18 present the data in forms which enable the determination of the N-year return values of significant wave height, H_s, and of the most probable value of the height of the highest individual wave in a 3-hour interval, $H_{max(3\ hours)}$, for N from 1 to 100.

Figure 13 gives the cumulative distribution of significant wave height for the whole year, plotted at half-metre intervals on the log-Normal scale;

Figure 14 presents the same data on the Weibull scale, and;

Figure 15 on the Fisher-Tippett type I scale.

Figure 16 gives the cumulative distribution of $H_{max(3\ hours)}$ for the whole year plotted at half-metre intervals on the log-Normal scale;

Figure 17 presents the same data on the Weibull scale, and;

Figure 18 on the Fisher-Tippett type I scale.

TABLE II

Results of extreme value analyses (Return values)

Heights are in metres

	Year	Log-Normal	F-T I	Weibull
H_s				
	1	17.5	17.5	17.5
	10	23	22	22
	20	24.5	23.5	23
	50	27	25	25
	100	29	26.5	26
$H_{max(3\ hours)}$				
	1	32	33	32
	10	42	41	39
	20	45	43	40.5
	50	48	46.5	43
	100	52	49	46

There is no theoretical justification for any of these distributions, but they do seem to work empirically. The data points above about 12m significant and 22m maximum wave height do not lie on a smooth curve, but best straight lines have been fitted by eye. There is no objective way of chocsing from these three methods, but it will be observed that the data are more nearly in a straight line on the Fisher-Tippett type I scale.

ii) Wave Periods

Value of T_z associated with the 50-year wave height

Extrapolations of zero-up-crossing periods, T_z, are unreliable for determining extreme-condition design parameters because many of the longer-period values relate to swell when wave height is not large. High waves generally have a significant-height steepness of between 1:15 and 1:20, and this applies in this data set (Figure 11). Accordingly, the zero-up-crossing period to be associated with the 50-year wave height can be deemed to lie between about 13 and 18 seconds.

The period of the individual 50-year return wave

This parameter has a broad probability distribution and is difficult to assess; according to Longuet-Higgins (1983) the median period of high individual waves coresponds to the mean spectral frequency, and so is $1.07T_z$, assuming a JONSWAP spectrum, (giving about 14 to 19 seconds for these data), but Bell (1972) suggests, from an analysis of North Sea instrumental data, a value of $1.28T_z$.

Clearly, for design purposes it is wise to consider a range of values.

(e) Persistence

Because the records are discontinuous, it is not possible to produce persistence diagrams for this station, although recent studies by Kuwashima and Hogben (1984) indicate that it might be possible to produce an empirically-derived distribution based on the scatter diagram, such as Figure 11.

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RESULTS OF THE MEASUREMENT PROGRAMME

JULIETT 2

(a) The most severe wave conditions

The highest value of H_1 in this analysis, actual wave height after correction for instrumental response, measured at OWS JULIETT was 20.3m (significant height 11.3m) with a mean zero-crossing period T_z of 11.6sec, at 18hr 12.2.73, although there were four other records with higher values of significant wave height. The second highest wave (H_1) was 20.1m with a mean zero-crossing period T_z of 11.4sec at 09hr on 14.2.73.

Values of significant wave height and the most probable value of the height of the highest wave in 3 hours (the recording interval) are normally derived statistically from the two measurements H_1 and H_2 (first and second highest wave) taken from the short analogue record. In general, errors caused by the statistical variations inherent in the short sample and the necessarily-rapid analytical techniques can be expected to cancel out for the bulk of the data, but for the very highest recorded waves there is a strong possibility that the highest wave on a record was itself the 3-hour (or even longer interval) wave. Accordingly, it is sensible to determine significant wave height by a more comprehensive method. This has been done for each of the five records showing the highest individual values of H_1, calculating the average height of the highest one-third of the crests, using excursions from the mean, and similarly with the average troughs, and then adding the two values to yield a more widely-based estimate of significant wave height. These values have replaced the mass-produced values in the original data set. As expected, the new values are slightly lower than the mass-produced ones. These five most severe (significant height) conditions were as given in Table III (page 16).

(b) Calms

There were no calms (defined as significant height of 0.5m or less); on only about 20 occasions did the significant height fall below 1 metre, the lowest calculated value being 0.78m. there was one memorable occasion in 1972 when it did not exceed 1 metre for ten consecutive measurements and this was, rather unexpectedly, in mid September close to the equinox.

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TABLE III

Records having the five largest values of Significant Wave Height
(Values derived from H_1 and H_2 are given in brackets)

Day No	Date	hr	T_z sec	HEIGHTS (in metres) Significant(H_s)	Highest on Record
43	12.02.73	21	12.3	12.4 (12.8)	18.6
45	14.02.73	09	11.4	12.3 (13.3)	20.1
23	23.01.75	09	11.2	11.7 (12.8)	19.4
19	19.01.75	12	10.3	11.6 (12.6)	20.0
43	12.02.73	18	11.6	11.3 (13.1)	20.3

(c) Seasonal and Annual Distributions

The results of the analysis of all the three-hourly records are shown in the figures, prepared using the IOS forms of presentation recommended for engineering purposes (Draper, 1966). Some of these figures give results for individual seasons defined as follows:

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

Note that in this analysis the leap year is ignored.

Figures 19-22 show the cumulative distribution of H_s and of $H_{max(3hours)}$ for each of the four seasons, and Figure 23 gives the distribution for the whole year. For example, Figure 19 shows that during the winter the significant wave height exceeded 5.0 metres for 50% of the time, while Figure 23 shows that a 3.2 metre significant wave height was exceeded for 50% of the entire year.

Figures 24-28 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 of T_z was least during the summer, at 7.5-8 seconds, and greatest during the winter at 9-9.5 seconds. The largest zero-crossing periods in the winter season approached 13.5 seconds, although swell in the summer slightly exceeded this value. The histograms show the smallest values of T_z to be about 5 seconds; the rapid attenuation of short waves

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with depth causes the Shipborne Wave Recorder pressure sensors to be insensitive at periods shorter than this.

Figure 29 is a scatter diagram showing the joint distribution throughout the year of significant wave height and zero-up-crossing period. For example, the most frequently-occurring combinations were waves with significant wave heights of between 2 and 3 metres and periods of between 7.5 and 8.5 seconds. These occurred for 11% of the time, or, since there are 2920 three-hour durations (and samples) in an average year, on about 320 occasions (if the range is extended to between 2 and 4 metres the occurrence is 18% and about 530 occasions).

Wave steepness is defined as the ratio of wave height : wave length; lines of constant significant wave height steepness 1:7, 1:10, 1:15, 1:20 and 1:40 are drawn on Figure 29 (wave length was computed using simple wave theory, i.e. $L=gT^2/2\pi$ where T is deemed to be the zero-crossing wave period T_z.

Figure 30 is a more detailed version of Figure 29 but it excludes the most severe conditions. Note that rounding can cause apparent differences of one in the totals within particular height and period ranges.

(d) Extreme Conditions

i) Wave Heights

Figures 31-36 present the data in forms which enable the determination of n-year return values of significant wave height, H_s, and of the most probable value of the height of the highest individual wave in a 3-hour interval, $H_{max(3hours)}$, for N from 1 to 100.

Figure 31 gives the cumulative distribution of significant wave height for the whole year, plotted at half-metre intervals on the log-Normal scale;

Figure 32 presents the same data on the Weibull scale, and;

Figure 33 on the Fisher-Tippett type I scale.

Figure 34 gives the cumulative distribution of $H_{max(3\ hours)}$ for the whole year plotted at half-metre intervals on the log-Normal scale;

Figure 35 presents the same data on the Weibull scale, and;

Figure 36 on the Fisher-Tippett type I scale.

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TABLE IV

Results of extreme value analyses (Return values)

Heights are in metres

	Year	Log-Normal	F-T I	Weibull
H_s				
	1	16.5	16	15.5
	10	22	19.5	19
	20	24	20.5	20
	50	26	22	21
	100	28.5	23.5	22
H_{max}(3 hours)				
	1	31	29.5	31
	10	41	36.5	37
	20	44	39	39
	50	47	42	41
	100	52	44	43

There is no theroretical justification for these distributions, but they do seem to work empirically. The best straight lines have been fitted by eye. There is no objective way of choosing from these three methods, but it will be observed that the data are more nearly in a straight line on the Fisher-Tippett type I scale.

ii) Wave Periods

Value of T_z associated with the 50-year wave height

Extrapolations of zero-up-crossing periods T_z are unreliable for determining extreme-condition design parameters because many of the longer-period values relate to swell when wave height is not large. High waves generally have a significant-height steepness of between 1:15 and 1:20, and this applies in this data set (Figure 29). Accordingly, the mean zero-up-crossing period to be associated with the 50-year wave height can be deemed to lie between about 13 and 18 seconds.

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The period of the individual 50-year return wave

This parameter has a broad probability distribution and is difficult to assess. According to Longuet-Higgins (1983) the median period of high individual waves corresponds to the mean spectral frequency, and so is $1.07T_z$ assuming a JONSWAP spectrum, (giving about 14 to 19 seconds for these data), but Bell (1972) suggests, from an analysis of North Sea instrumental data, a value of $1.28T_z$. Clearly, for design purposes it is wise to consider a range of values.

(e) Persistence

Because the records are discontinuous, it is not possible to produce persistence diagrams for this station, although recent studies by Kuwashima and Hogben (1984) indicate that it might be possible to produce an empirically-derived distribution based on the scatter diagram, such as Figure 29.

DISCUSSION ON PRESENT DATA AND THEIR COMPARISONS WITH EARLIER DATA

In the earlier analyses it was difficult to distinguish between the INDIA and JULIETT (INDIA 1 and JULIETT 1) data sets, but this is not so with the newer measurements. In comparison with the earlier data, those in this report (INDIA 2 and JULIETT 2) suggest a markedly more severe climate. At JULIETT the all-year average increase in median wave height since the sixties is 11% and at INDIA it is 27%, with the latter's 'winter' of January, February and March showing an increase of 36%.

The ratios of median wave height exceedance are as follows:

	INDIA2/INDIA1	JULIETT2/JULIETT1
'Year'	1.27	1.11
Winter	1.36	1.16
Spring	1.25	1.00
Summer	1.31	1.21
Autumn	1.16	1.06

A difference, but almost certainly an insignificant one, is that the original 'winters' started on 23 December and ended on 22 March, whereas now a winter is deemed to start on 1 January and end on 31 March. Wave heights are generally greater at the end of December than in the last week of March, so that, if anything, the series 1 winter data should have been slightly more severe than in this second series.

It is apparent from a comparison of the scatter diagrams (Figures 11 and 29) with their equivalents in the INDIA 1 and JULIETT 1 data publications that the mode of the period distribution has decreased from about 8.75 seconds in INDIA 1 and JULIETT 1 to about 8.25 seconds in INDIA 2 and JULIETT 2 (a decrease of about 6%). It is difficult to accept that this is a real change, especially as the wave heights seem to have increased, but as the chart speed was governed by the frequency of the ships' generators it is just possible that there was a permanent change in both ships' systems in the same sense between about 1965 and 1970. However, the ships' engineers feel that the frequencies rarely deviated by this amount and that the mean values would have been close to the specified 50Hz. It is also possible that this change in apparent period is an artefact of the manual method of analysis, but it is difficult to understand how a change as large as 6% could occur from this cause. The first effect of a slowing of the chart speed is a reduction of the apparent period of the waves, and therefore an increase in the apparent number of waves at the site. This difference can be seen in Table V (page 26).

It is of interest that the series 2 data are close in wave period to those of OWS LIMA wave data (Gleason, 1985) measured after INDIA and JULIETT were terminated. About two thirds of the LIMA data were from records which were taken with an accurately-controlled chart speed, so it can be concluded that the INDIA and JULIETT series 2 data are more reliable in terms of period than are series 1. From this premise it is reasonable to conclude that height data from the INDIA and JULIETT series 1 data are underestimates by perhaps 2 or 3 percent, because of the changes in frequency response of the instrument over the frequency range.

The changes in the maxima of the wave height distributions are in good agreement with the changes in the median values; for example, a comparison of the annual scatter diagrams shows that the 'summit' of the contours on INDIA 1 lies at about 7.7 feet (2.3m), and on INDIA 2 it lies just below 3m, an increase of about 30%. Similarly, the maximum of the 20 parts/thousand level contour is at about 12 feet (3.7m) on INDIA 1 and about 5m on INDIA 2, an increase of about 35%; the maximum of the 30 parts/thousand level contour is at about 10 feet (3m) on INDIA 1 and 4m on INDIA 2, an increase of about 30%.

CHECKS MADE ON THE CLIMATE, INSTRUMENTS AND ANALYSES

Because of these significant increases in average wave heights at INDIA and JULIETT in the early seventies compared with the figures previously published of records taken in the early sixties, it became necessary to investigate all aspects relevant to both sets of measurements and analyses.

Briefly, no discrepancy has been found.

Recordings were made on the same actual instruments, on the same type of chart and on the same ships which occupied one station or the other on an apparently random basis; it was not until the mid seventies, after INDIA and JULIETT had been abandoned, that the recorders were superseded by transistorised versions. Certainly, there is no preponderance of occupation of one ship at either location, so the difference in increase of 27% at INDIA and 11% at JULIETT cannot be attributed to a faulty calibration of one particular instrument. The principal instrumental change between series 1 and series 2 has been an increase in chart scale to accommodate extreme waves which occasionally occur, but this cannot account for any change in sensitivity. There was only a small amount of data from WEATHER EXPLORER (in series 1 only), and none of these came from the winter. The first reaction was that the climate had become more severe. A check on the wind conditions at INDIA for the winter months when the bulk of the severe-weather data was obtained shows that there was no significant change in the mean wind speeds. This is a simple check, but it seems unlikely that it would not show up some difference in the winter when waves at INDIA appear to be 36% higher, which would mean perhaps a 20% increase in wind speed. However, it is just conceivable that by chance the wave measurements in series 1 were made at times when the winds were less severe, or that the wave measurements in series 2 were made at times when winds were more severe, or a combination of both, so the wind speeds at the actual times of the wave measurements of both series at both stations were investigated. This shows that the populations of the wind data were virtually the same in both series from each station, whereas for significant wave heights H_s the differences are significant at JULIETT and highly significant at INDIA. The checks were repeated to compare waves with winds six hours previous to each wave measurement, and the results were the same. Detailed results of these investigations are given in the Appendix.

Even if in the later (series 2) measurements there were to have been much more swell than usual arriving from elsewhere it is most unlikely that it would have affected the mean wave heights to a noticeable extent; this is because the combined wave height is proportional to the square root of the sum of the squares of the separate systems. For example, if the local wave field has a height of 3 units and then a 1-unit high swell-wave train comes along, the combined height is only 3.16 units high, a factor of 1.05. The winter increase at INDIA by a factor of 1.36 would have required a swell of almost the same height as the locally-generated waves and this is, almost by definition, impossible unless the rest of the Atlantic had been covered with storms very much more ferocious than those at INDIA - an unlikely situation.

The next aspect to come under scrutiny was the instrument calibration. The very earliest calibrations were not adequately recorded; in particular this concerns the actual settings of the sensitivity controls on the instruments during service. However, all controls were in a very inaccessible position in service and were locked, and all servicing until the mid sixties was undertaken by the present author personally who feels that there were no sizeable errors anywhere in the procedure. It was a matter of pride that considerable care was always taken to achieve the best possible calibrations. As time progressed, improved notes were made and kept, and by about 1960 the system was adequately standardized and recorded. The laid-down procedures were followed without problems by subsequent engineers, overall responsibility still being with the present author until 1974. All relevant calibration sheets have recently been checked by present engineering staff and no error has come to light. The bulk of the data in the earlier analyses had come from the sixties; only a few gap-filling records were of earlier date.

The only other variable has been the change in chart scales from 50 to 60 feet and then to 80 feet, followed by metrication which occurred after these data sets had been completed. There is no evidence that wrong charts were used either in calibration or in service (all checks undertaken show that the correct ones were indeed used at all times). It is difficult to see how a change in overall sensitivity, and therefore in chart scale, can alter the sensitivity to either small or large waves. In the earlier days the larger wave crests and troughs were obviously running more often into the more non-linear parts of the chart recorder, and it might be arguable that it would consequently under-read on big waves, but the chart itself is highly non-linear and almost certainly copes with that problem. The accuracy of the entire system out to the chart limits was one of the routine checks during calibration.

A further check was to calculate all the parameters from the early (INDIA 1 and JULIETT 1) analyses, starting with a check on the numbers taken from the chart records, and then using the present computer program. Although occasional errors were shown to have occurred in the early work, the bulk of the early calculations, performed on hand calculators, were close to their proper values; errors which were identified were random and seemed to cancel out, so the overall picture has not changed at all.

There is only one other Shipborne Wave Recorder station which was in operation around 1960 and also in the early seventies, and that is Sevenstones, off Land's End; in an analysis of several years' wave data from the late sixties and early seventies, Fortnum and Tann (1977) have shown that heights (at the 50% level) show an 11% increase on the values for 1962 (Draper and Fricker, 1965) which was an 'average' year, wind-wise. This is the same increase as at JULIETT. Challenor (private communication) has significance-tested the 1962 data to see if they are part of the same family as the later data, and he cannot identify any fundamental difference.

An earlier but independent source of wave data, visual observations published in 1963 in the Oceanographic Atlas of the North Atlantic Ocean, suggested that the average wave height at INDIA was 4% lower than that at JULIETT, although in any particular named month (averaged over many years) sometimes the average wave height was greater at one station and sometimes at the other. In this Atlas in each 5 degree square there were typically 500 to 1000 visual observations per calendar month, so this amount of random scatter can be expected. Previously, it seemed from instrumental measurements and from the Atlas that the climates at the two stations were very much the same. The picture now seems to have changed.

In a study of changes in the wind and wave regime of the North Sea, Lamb and Weiss (1979) show that there was a continued increase in wave heights from 1950 to the 1960s, followed by a slight decrease to the 1970s. The largest increase (but not the largest waves) occurred in the south-eastern area of the North Sea. Although these changes are in the opposite sense to those at INDIA and JULIETT, it does demonstrate that significant changes can and do occur. In the North Sea it is postulated that the changes might be due to a (demonstrable) increase in the frequency of occurrence of northerly winds at the expense of westerlies. It is difficult to understand how a change in the distribution of wind directions, but not speeds, in the middle of the North East Atlantic where all fetches are large, can affect the average wave height. It could have been explained if the average duration of high wind speeds had increased, as it would have resulted in more-fully-developed seas, but an analysis of data provided by the Meteorological Office of winds at OWS INDIA for the years 1960-64 and 1970-74 shows that the average duration of high wind speeds decreased from the sixties to the seventies, the opposite sense to that required to explain the change in wave conditions.

Lamb and Weiss also present a Gale Index Survey for the British Isles and Eastern North Atlantic from 1880 to 1977 in which they show that the number of days of gale per year from 1965-77 was higher than in any other period since 1889, but not quite as high as in 1880-89 (their page 22, Table 1 and Figure 6). It is possible therefore that in the early seventies the waves at INDIA and JULIETT were also more severe than in the rest of this century. The value given for 1960-65 is markedly the lowest for this century, but Lamb and Weiss have major reservations about its validity as that was the time when computer-automated map drawing was introduced, and the pressure gradients may have been unrealistically smoothed.

In a study, based on visual observations of wave height, of the longer-term changes in wave conditions of the North Atlantic from 1970 to 1982, H.J.A. Neu (1984) concluded that there are large variations in wave height from one year to another ranging from -25% to +45% of the mean. This is therefore greater than the differences occurring in these two measured data sets. Unfortunately, Neu does not present an analysis of conditions in the early sixties, neither does he present any evidence of changes in wind speed over the period which he studied; it seems improbable that such changes in wave height could occur without a commensurate change in wind speed, but this is exactly the situation which seems to have occurred at INDIA and JULIETT from the sixties to the seventies and where, at the Weather Ship Stations at least, the winds had not noticeably changed. Visual observations of winter wave heights from the weather ships themselves at station INDIA show an increase of only 5% from the early sixties to the early seventies. What is perhaps more alarming is that Neu maintains that there was a continuous increase in wave heights (except, mercifully, in the more severe wave conditions in the Eastern North Atlantic) from 1970 to 1982. Perhaps that trend had started by the early sixties, but if so it is difficult to believe that it has not by now made itself more evident to mariners in other ways.

METHODS USED IN THE CALCULATION OF EXTREMES

In the analysis of the two data sets, extreme conditions were estimated using four different methods, Log-Normal; Fisher-Tippett type I; Weibull; and Battjes. It was observed that the Battjes method (1972) was extremely sensitive to the highest individual records; omission of the one highest measured value in the INDIA 2 series results in a reduction of 1.5m in the estimated value of the 50-year return wave height. Accordingly, this method has been excluded from the study. A presentation of the Battjes results is given in Figure 37; note that JULIETT 1 and JULIETT 2 are indistinguishable on this plot, a somewhat surprising result. This demonstrates the differences between the two stations, and also the effect of removing the one highest value from the INDIA 2 data.

Table V presents the number of waves derived by the Battjes method for each series, and gives the best estimate of the 50-year return value of individual wave height using a visual linear fit to the curves in Figure 37 (values to the nearest half metre).

TABLE V

	No of waves/year	50-year wave height (m)
INDIA		
I1	3.41×10^6	37.0
I2	3.76×10^6	41.5
I2mod	3.76×10^6	40.0 (the one highest wave omitted)
JULIETT		
J1	3.39×10^6	35.0
J2	3.70×10^6	35.0

Refer also to Tables II (page 13) and IV (page 18) for Log-Normal, Fisher-Tippett I and Weibull extrapolations. The JULIETT results in Table V are not recommended for design.

CONCLUSIONS

The conclusion is that there is no obvious meteorological or artefactual explanation for the apparent change in wave climate from the nineteen sixties to the nineteen seventies. It might just be within the realms of possibility that the necessarily-short instrumental samples could have produced the variability, but measurements made subsequently on station LIMA (nearer to INDIA than to JULIETT) (Gleason, 1985) bear more similarity to INDIA 2 than to the older measurements or, indeed, to JULIETT 2. On this basis, considering all available evidence, it seems likely that the severity of wave conditions in the North Atlantic at about 20°W and between 52°N and 59°N had changed from the early sixties to the early seventies, both in absolute values and in geographic distribution.

From the evidence of the INDIA and JULIETT measurements alone it may be unjustified to conclude that there is an upward trend; what we have seen could be just two 'spot' samples of a randomly-varying signal, but this cannot disprove Neu's contention that there is such a trend especially so as the subsequent measurements at LIMA do support the increased severity described by the INDIA 2 and JULIETT 2 data. The only firm conclusions are that North East Atlantic wave conditions really can be more severe and more variable than had previously been accepted, and that we shall need to obtain many more measurements before we can truly claim to know the wave climate in this area to an acceptable level. Even so, the problem of climatic variation is one which must be borne in mind with due caution.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the Meteorological Office for permitting the fitting of Shipborne Wave Recorders to Ocean Weather Ships ADVISER and REPORTER, and his thanks to those who, over the years, maintained the instruments and obtained the records. This applies especially to Mr. E. Binner, Shore Meteorologist, who helped enormously in a multitude of ways throughout the entire period, and Mr. J.S. Driver (now of J.S. Driver SEAWAVE Services) who maintained the instruments in tip-top condition. The author is also grateful to colleagues in the Institute of Oceanographic Sciences who helped with the instrumentation, analyzed the records and wrote and ran the computer programs, and also those, D.J.T. Carter in particular, who have commented constructively on this draft, Dr. A.R. Tabor who undertook much of the data handling, and P.G. Challenor who made the wind and wave comparisons described in the Appendix. The help of Professor H.H. Lamb on the problem of the relative severity of the measurement period, and the Meteorological Office in the provision of comparative environmental data, are very much appreciated. Some of the work undertaken in this study has been funded by the Department of Energy.

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Coding on Figures:

I1	INDIA data 1955-1965
I2	INDIA data 1970-1975
I2 Mod	I2 data less the one highest value
J1	JULIETT data 1955-1965
J2	JULIETT data 1970-1975
J12	J1 and J2 combined data

APPENDIX

An investigation into the relationships between wave heights, wind speeds and air-sea temperature differences for Series 1 and 2 INDIA and JULIETT data

by

P.G. Challenor, IOS Wormley

Wave heights and wind speeds

Because the variance of the observations changes throughout the year it was decided to analyse the natural logarithm of both wave height and wind speed; the monthly means and variances of log H_s and log u are shown in Table AI. Taking logs has had the effect of making the variances approximately constant. Once equality of variances has been obtained, a paired t-test can be performed; for example, the sum of the differences between the two years divided by their standard deviation has a t-distribution with 12 degrees of freedom if there is no difference between the two years. Performing this test on the data in Table AI gives similar results for both I and J: there are significant differences in H_s between the two series but no significant difference in wind speed.

Wave heights and temperatures

Table AII shows the means and variances of log (Visual wave height) [derived from (H_{max} + H_{swell})] and air-sea temperature difference. The results for visual wave height are the same as for H_s measured by the Shipborne Wave Recorder, but on Weather Ships it is likely that the reporting officers 'calibrate' themselves against the wave recording instrument, so it would be dangerous to assume that the increase in visually-reported wave heights is confirmation of the apparent change in wave climate.

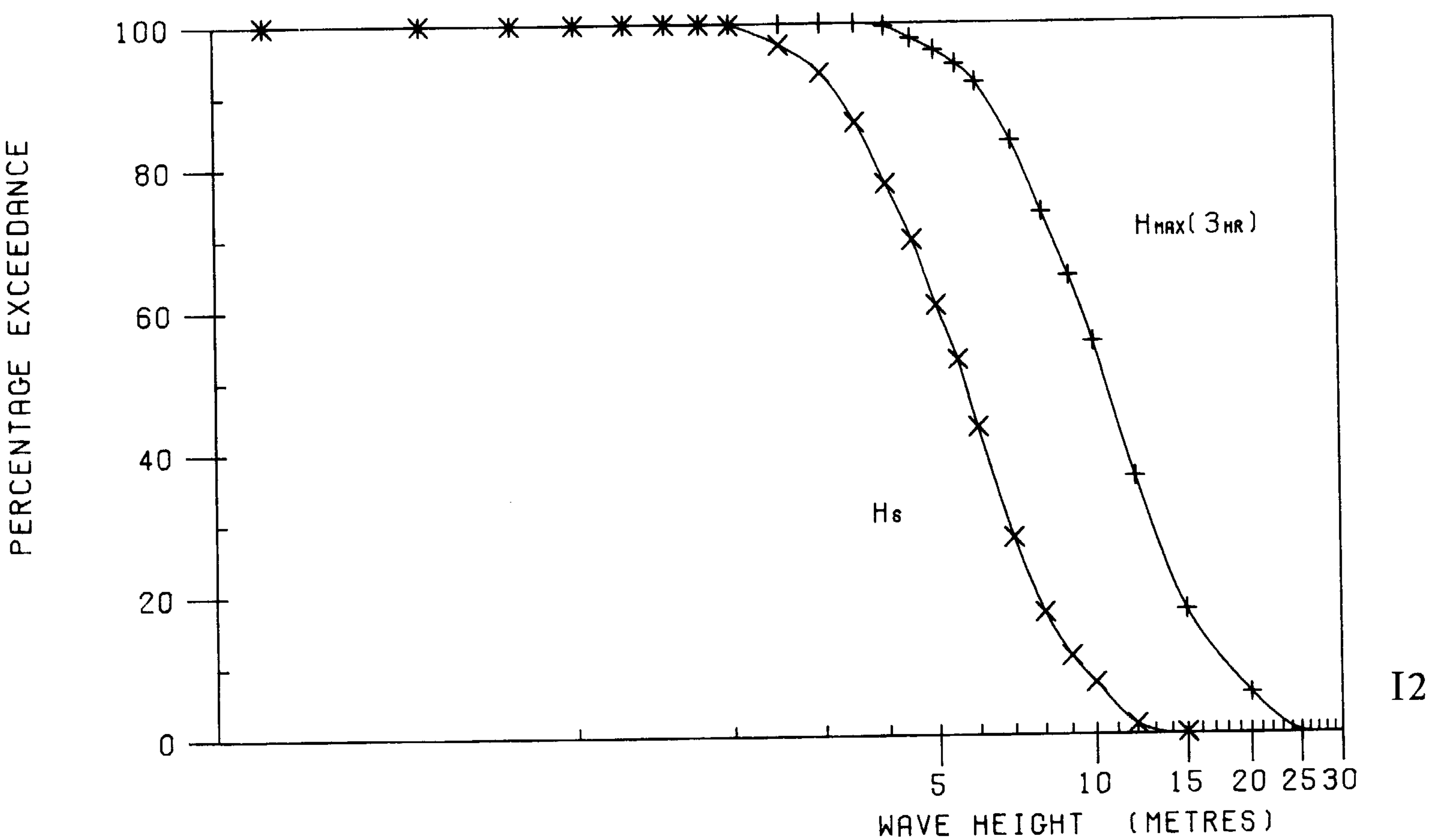
Unfortunately, a log transformation cannot be used on air-sea temperature difference and therefore it is not possible to perform a t-test. However, visual inspection of the table shows little difference between the earlier and later sets at each station.

	INDIA								JULIETT							
	$l_n(H_s)$				$l_n(U)$				$l_n(H_s)$				$l_n(U)$			
	Year 1		Year 2		Year 1		Year 2		Year 1		Year 2		Year 1		Year 2	
	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var
Jan	1.41	0.28	1.82	0.10	3.01	0.39	3.08	0.28	1.36	0.17	1.78	0.80	3.16	0.10	3.07	0.25
Feb	1.91	0.14	1.85	0.12	3.31	0.28	3.27	0.19	1.56	0.13	1.70	0.13	3.17	0.25	3.27	0.15
Mar	1.33	0.11	1.47	0.16	3.07	0.27	3.00	0.38	1.60	0.09	1.40	0.16	3.02	0.24	3.04	0.39
Apr	0.93	0.26	1.26	0.17	2.83	0.25	2.82	0.25	1.06	0.19	1.03	0.17	2.96	0.34	2.87	0.19
May	0.71	0.37	0.98	0.17	2.71	0.29	2.67	0.32	0.58	0.43	0.88	0.11	2.45	0.26	2.75	0.30
Jun	0.85	0.35	1.02	0.13	2.83	0.30	2.80	0.21	0.66	0.34	0.86	0.21	2.85	0.29	2.72	0.26
Jul	0.67	0.34	0.96	0.20	2.62	0.38	2.65	0.23	0.50	0.15	0.81	0.12	2.63	0.29	2.65	0.23
Aug	0.51	0.26	0.86	0.16	2.43	0.36	2.69	0.22	0.95	0.24	0.79	0.10	2.56	0.41	2.59	0.28
Sep	1.00	0.23	1.14	0.23	2.85	0.35	2.75	0.36	0.81	0.28	1.07	0.26	2.81	0.24	2.73	0.44
Oct	1.05	0.18	1.27	0.22	2.81	0.32	2.87	0.28	0.86	0.09	1.02	0.13	2.81	0.30	2.77	0.27
Nov	1.26	0.31	1.31	0.09	2.90	0.32	2.81	0.34,	1.11	0.31	1.34	0.13	2.89	0.32	2.93	0.32
Dec	1.32	0.14	1.64	0.13	2.92	0.21	3.11	0.20	1.47	0.21	1.61	0.10	3.12	0.21	3.14	0.21

TABLE AI Means and variances of log significant wave height and log wind speed, by month

	INDIA								JULIETT							
	$l_n(H_{vis})$				T - SST				$l_n(H_{vis})$				T - SST			
	Year 1		Year 2		Year 1		Year 2		Year 1		Year 2		Year 1		Year 2	
	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var	Mean	Var
Jan	1.47	0.40	1.87	0.14	-1.93	2.57	-3.28	4.21	1.52	0.06	1.81	0.16	-1.97	3.20	-2.96	3.92
Feb	2.01	0.33	1.84	0.15	-3.29	5.23	-2.60	8.00	1.58	0.18	1.84	0.14	-1.12	1.50	-2.49	8.34
Mar	1.32	0.18	1.50	0.25	-2.40	4.23	-2.55	3.97	1.50	0.30	1.54	0.29	-1.27	2.64	-2.34	3.86
Apr	1.25	0.07	1.36	0.22	-1.66	3.58	-1.15	5.86	1.40	0.24	1.40	0.17	-1.02	1.80	-0.85	5.91
May	0.78	0.57	1.01	0.28	-0.62	1.52	-0.64	1.25	-0.13	0.33	1.11	0.19	-0.57	0.58	-0.76	1.31
Jun	1.21	0.34	1.20	0.13	-0.38	0.70	-0.50	0.95	0.62	0.20	1.01	0.24	-1.00	1.14	-0.57	0.70
Jul	1.03	0.23	1.08	0.21	-0.21	0.77	0.03	0.63	0.95	0.14	1.10	0.20	-0.95	0.30	-0.02	0.59
Aug	0.69	0.29	0.95	0.19	0.04	0.66	-0.28	0.67	0.93	0.24	0.84	0.23	-0.62	0.50	-0.43	0.75
Sep	1.27	0.30	1.21	0.22	-0.99	0.83	-0.93	1.47	1.26	0.24	1.22	0.38	-1.19	0.61	-0.57	1.34
Oct	1.06	0.25	1.38	0.23	-0.44	1.03	-1.06	2.69	1.13	0.10	1.25	0.23	-1.05	0.53	-1.30	2.90
Nov	1.13	0.27	1.44	0.17	-1.17	4.00	-2.76	5.34	1.54	0.08	1.47	0.17	-1.56	1.70	-2.82	5.84
Dec	1.45	0.18	1.64	0.21	-1.99	3.93	-1.88	3.74	1.36	0.17	1.83	0.20	-2.94	2.42	-2.69	3.92

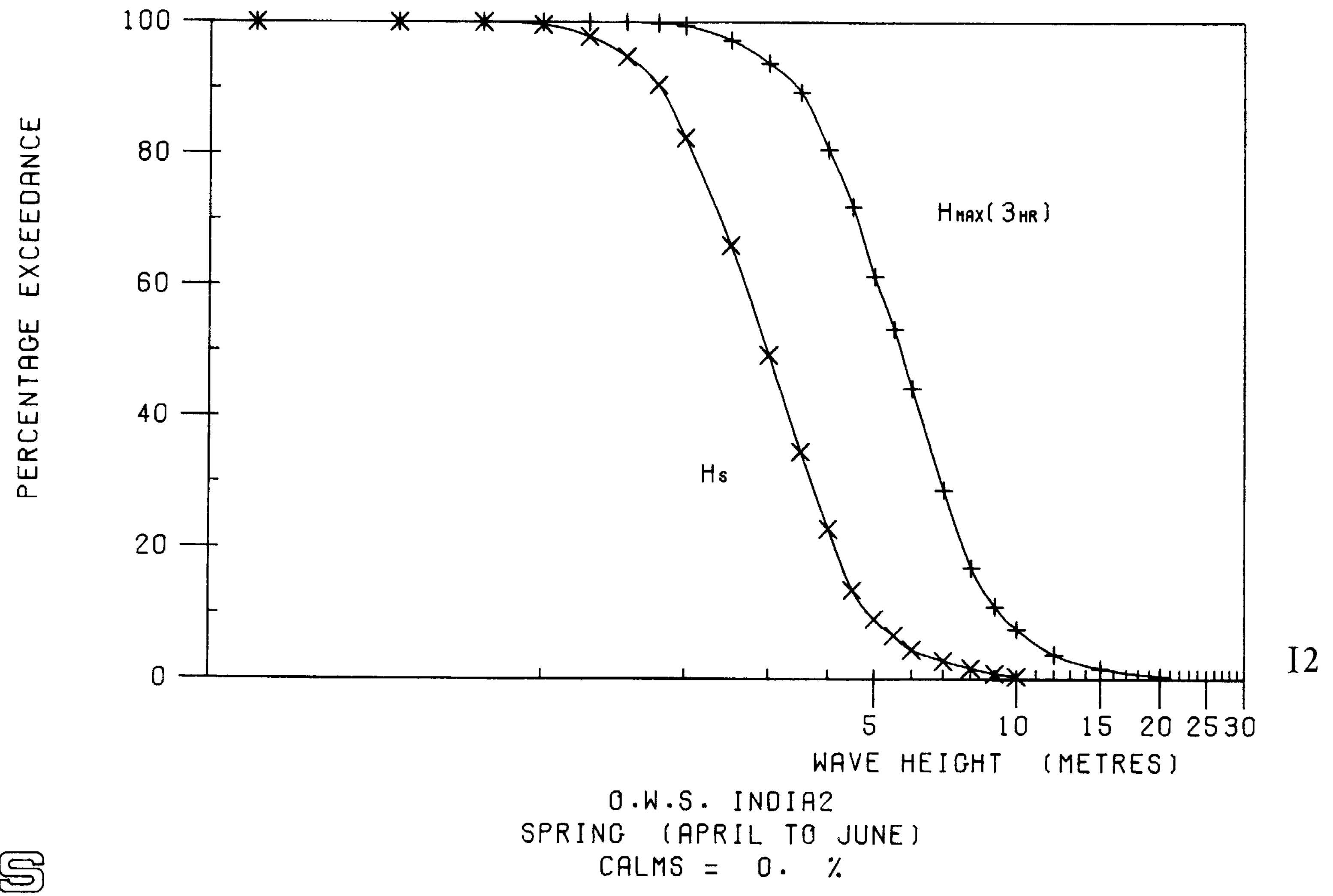
TABLE AII Means and variances of log visual wave height and air-sea temperature difference, by months



O.W.S. INDIA2
WINTER (JANUARY TO MARCH)
CALMS = 0. %

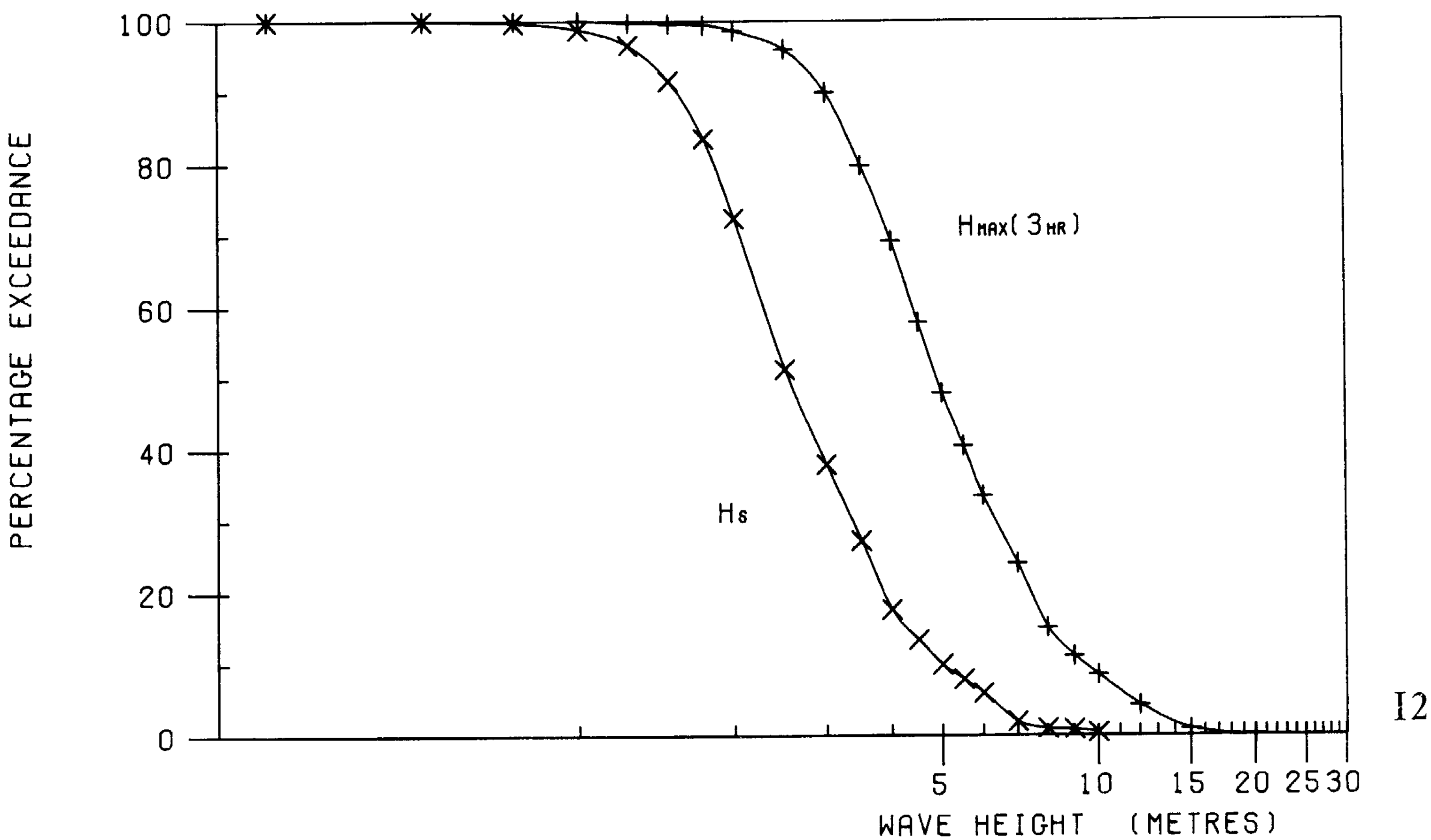
MIAS

Fig. 1


PERCENTAGE EXCEEDANCE
100
80
60
40
20
0
5
10
15
20
25
30
WAVE HEIGHT (METRES)
HMAX(3HR)
Hs
I2
O.W.S. INDIA2
SPRING (APRIL TO JUNE)
CALMS = 0. %

MIAS

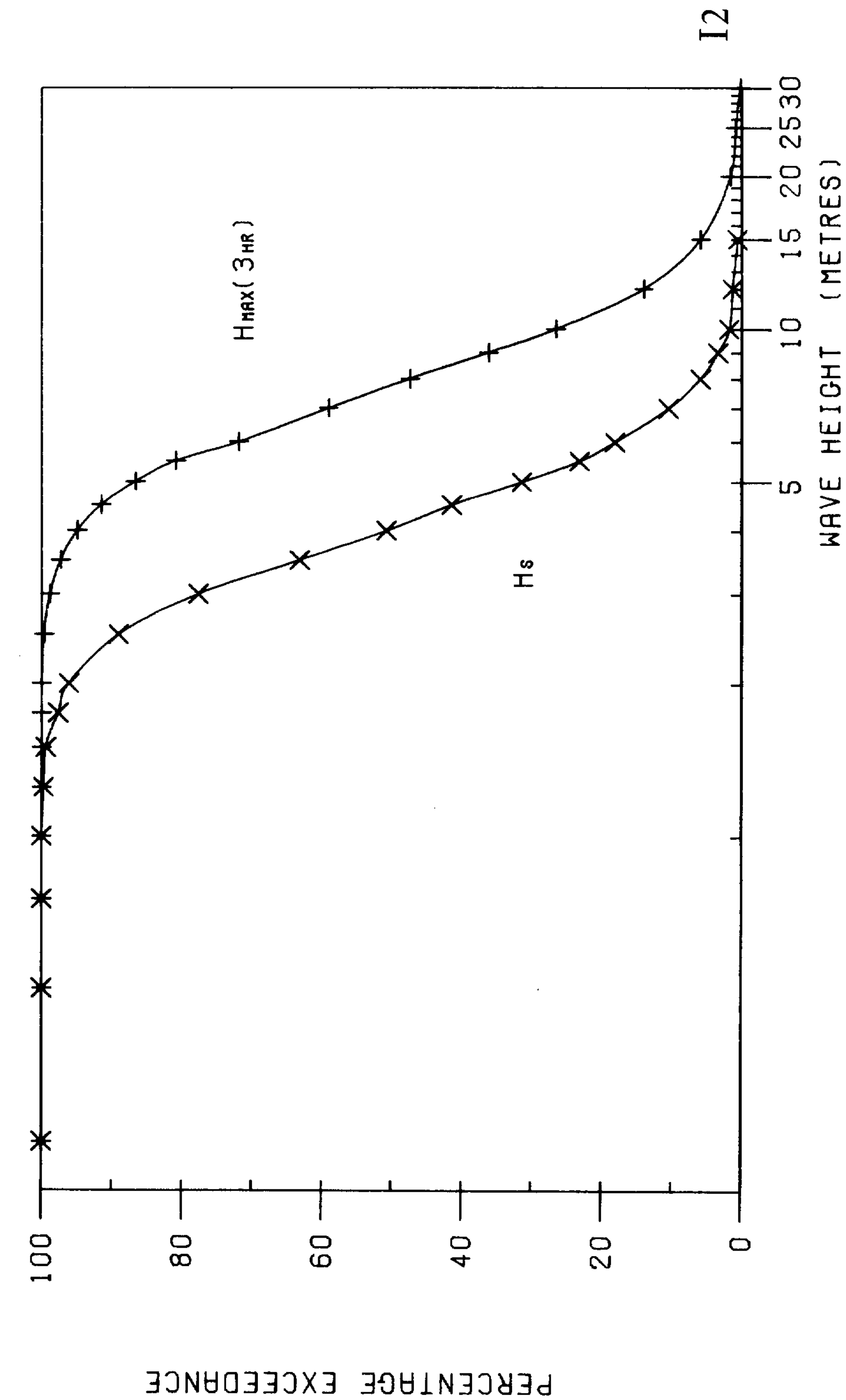
Fig. 2



O.W.S. INDIA2
SUMMER (JULY TO SEPTEMBER)
CALMS = 0. %

MIAS

Fig. 3



O.W.S. INDIA2
AUTUMN (OCTOBER TO DECEMBER)
CALMS = 0. %

Fig. 4

MIAS

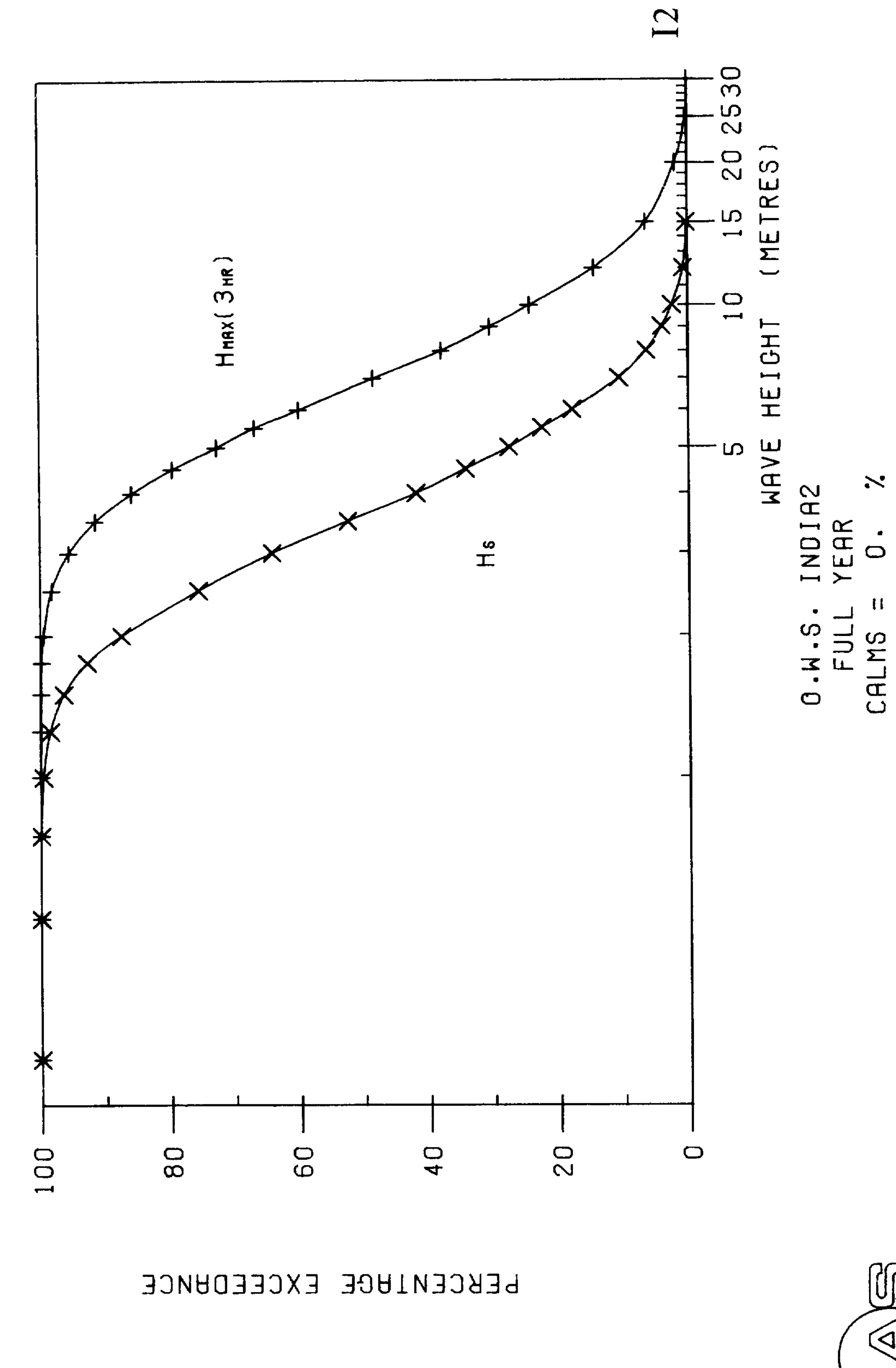
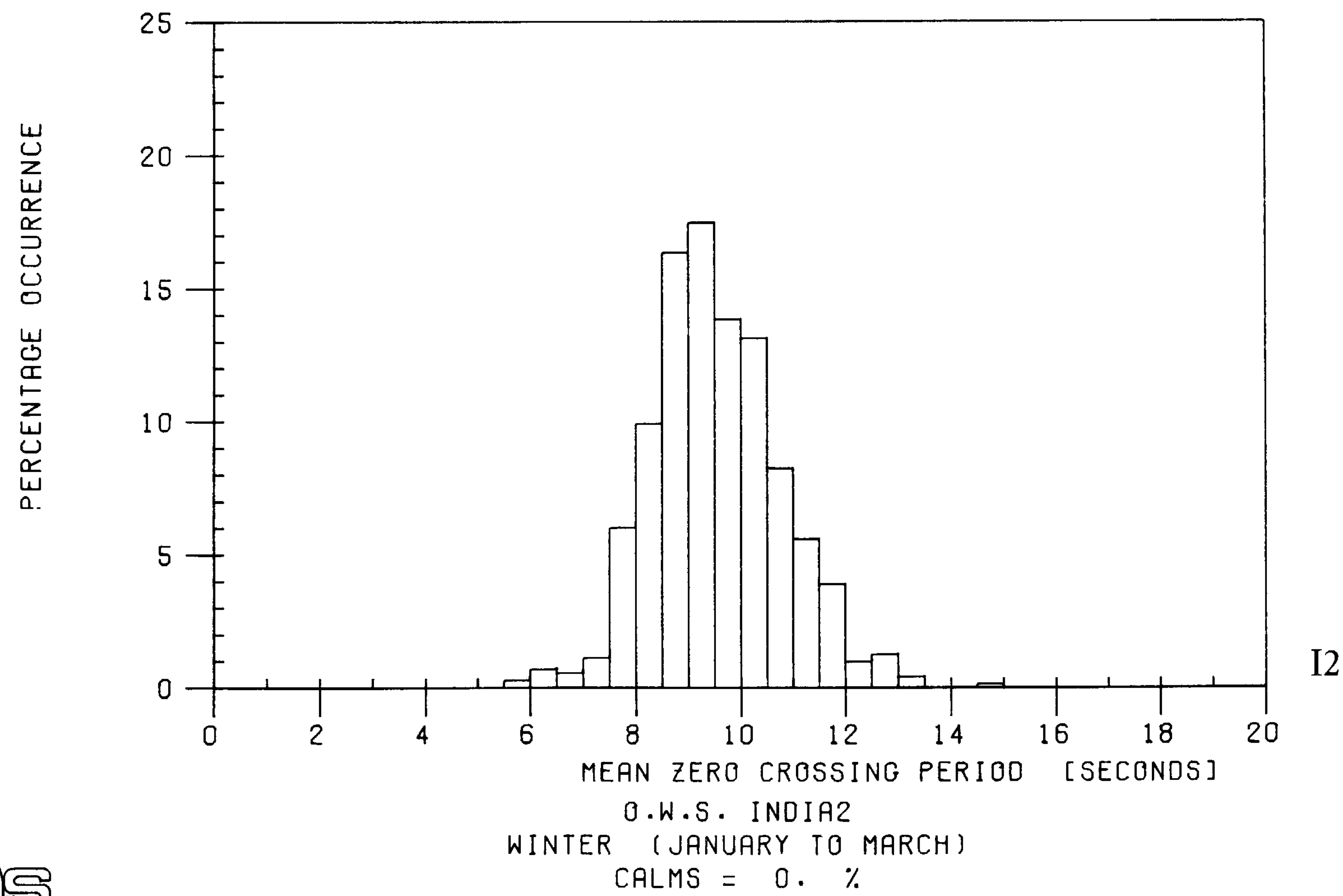
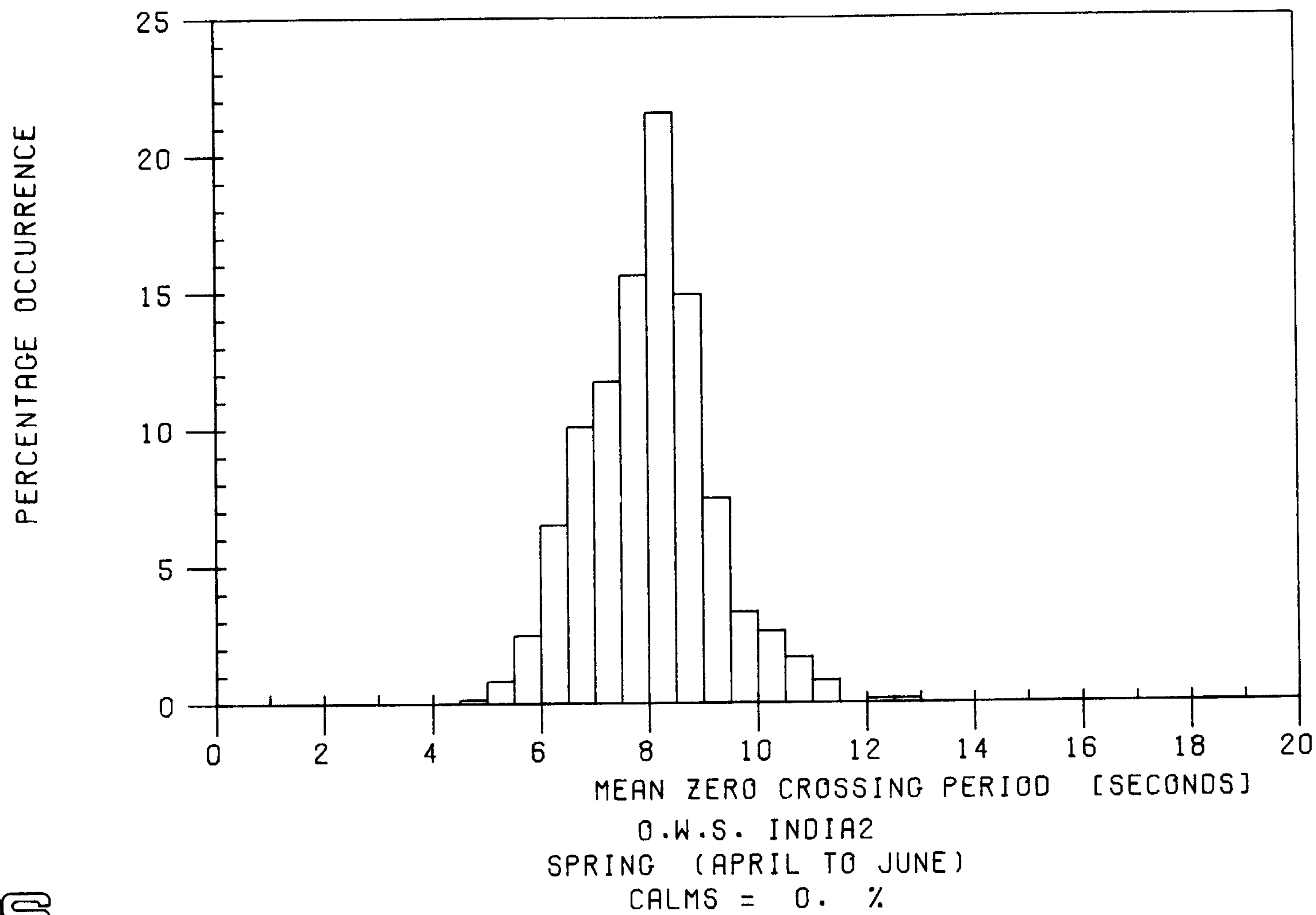

I2
HMAX(3HR)
Hs
100
80
60
40
20
0
PERCENTAGE EXCEEDANCE
5
10
15
20
25
30
WAVE HEIGHT (METRES)
O.W.S. INDIA2
FULL YEAR
CALMS = 0. %

Fig. 5


PERCENTAGE OCCURRENCE
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
I2
MEAN ZERO CROSSING PERIOD [SECONDS]
O.W.S. INDIA2
WINTER (JANUARY TO MARCH)
CALMS = 0. %

MIAS

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]
O.W.S. INDIA2
SPRING (APRIL TO JUNE)
CALMS = 0. %

I2

MIAS

Fig. 7

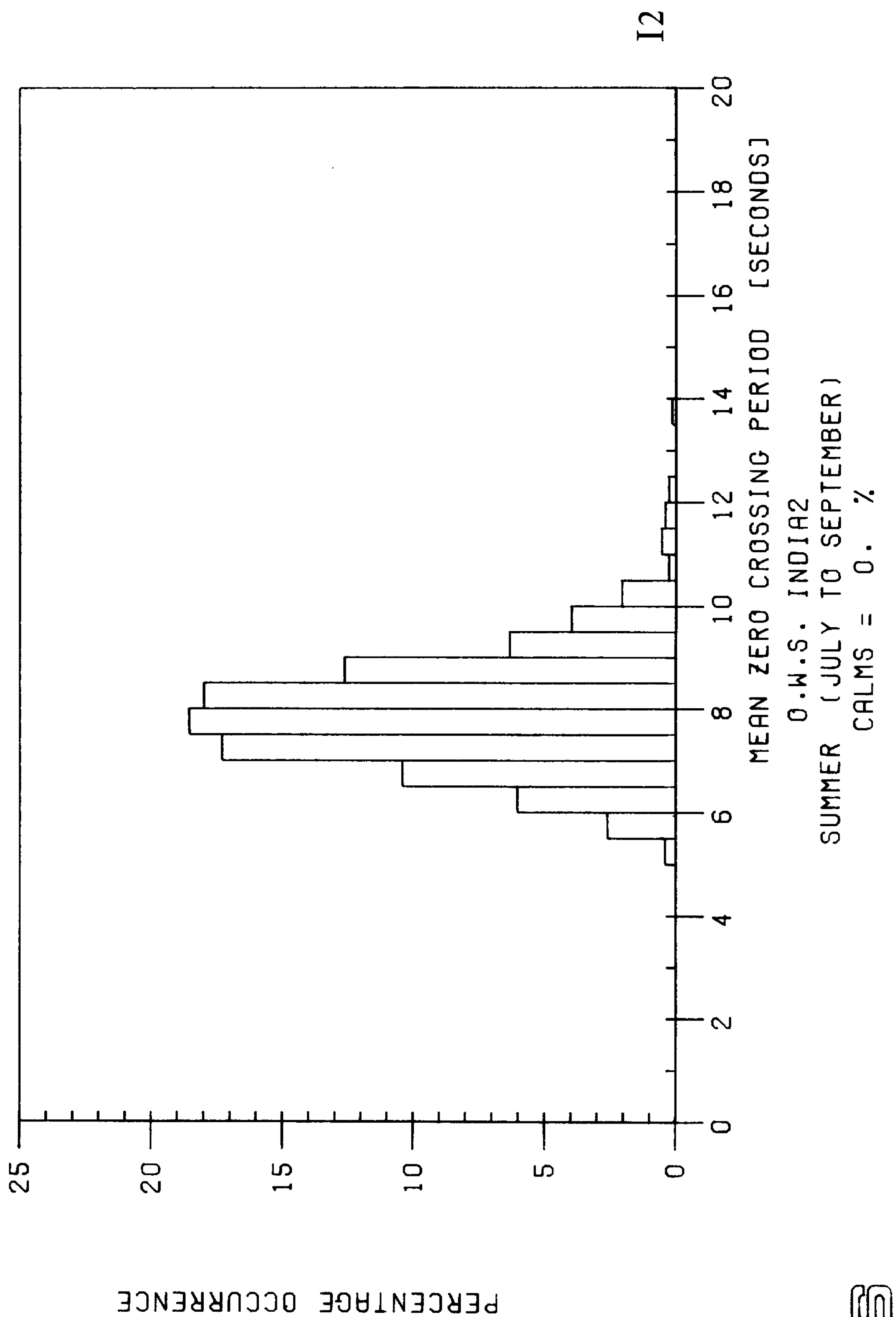
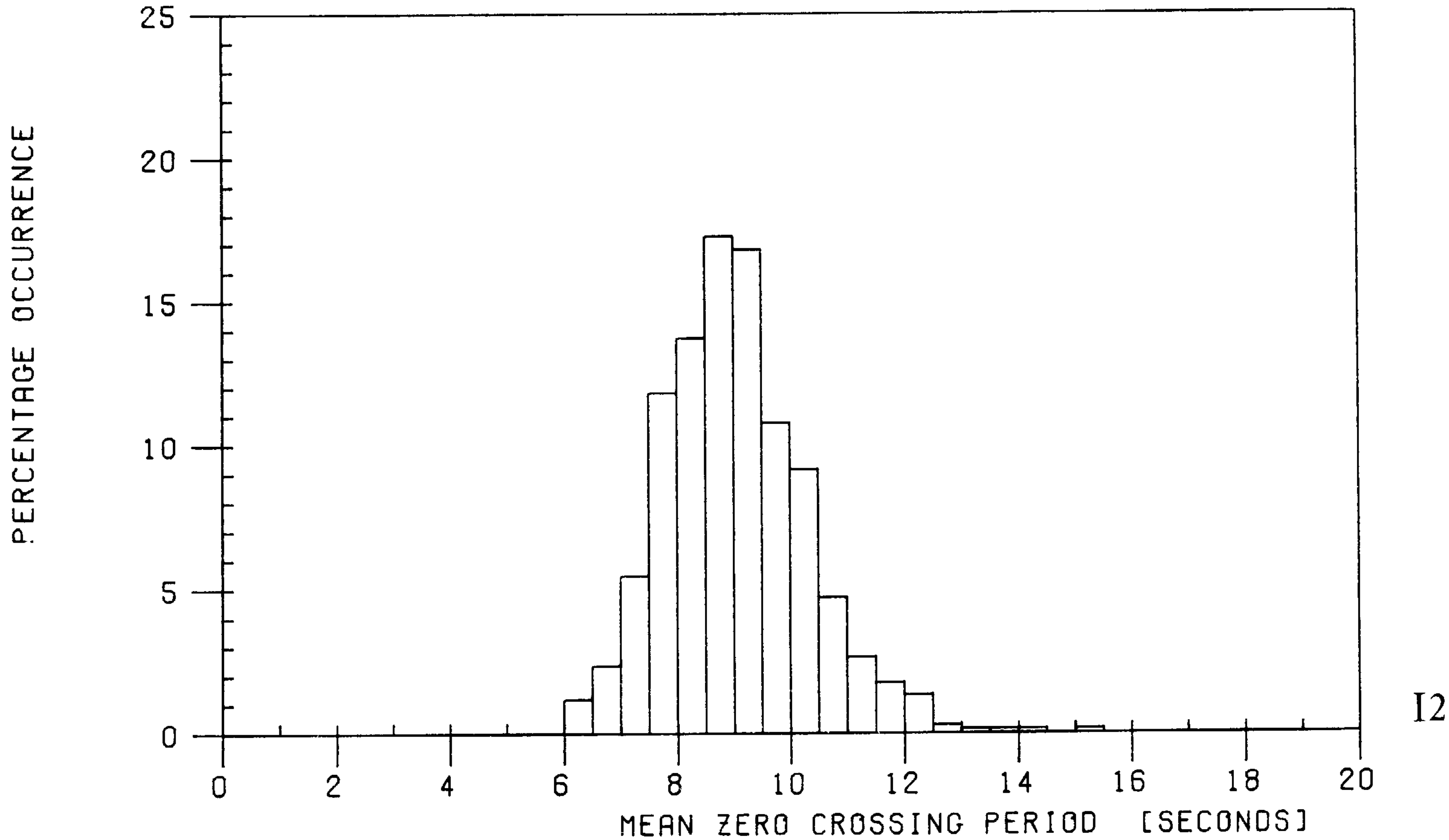

I2
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
0
5
10
15
20
25
PERCENTAGE OCCURRENCE
O.W.S. INDIA2
SUMMER (JULY TO SEPTEMBER)
CALMS = 0. %

Fig.8



O.W.S. INDIA2
AUTUMN (OCTOBER TO DECEMBER)
CALMS = 0. %

Fig.9

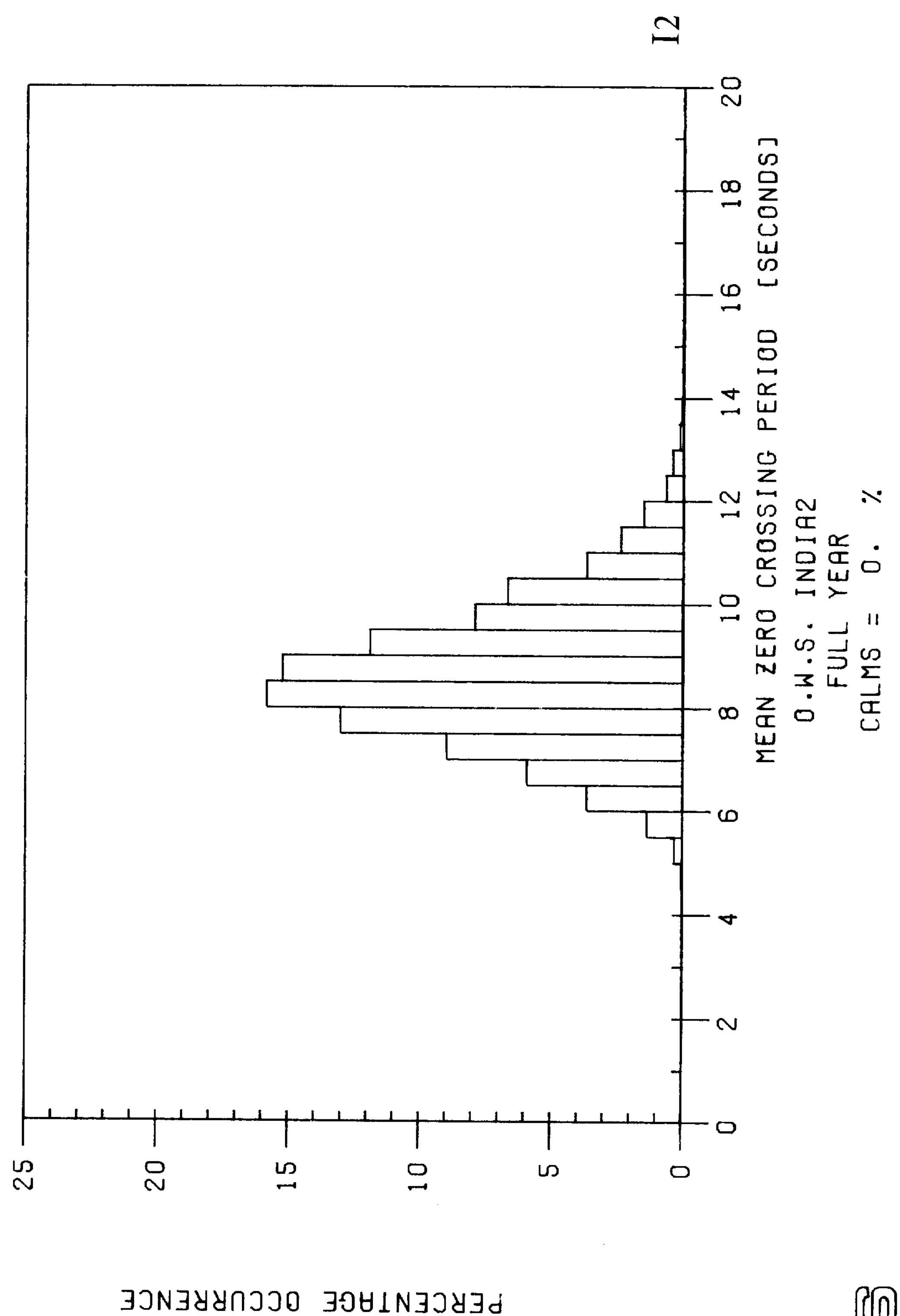
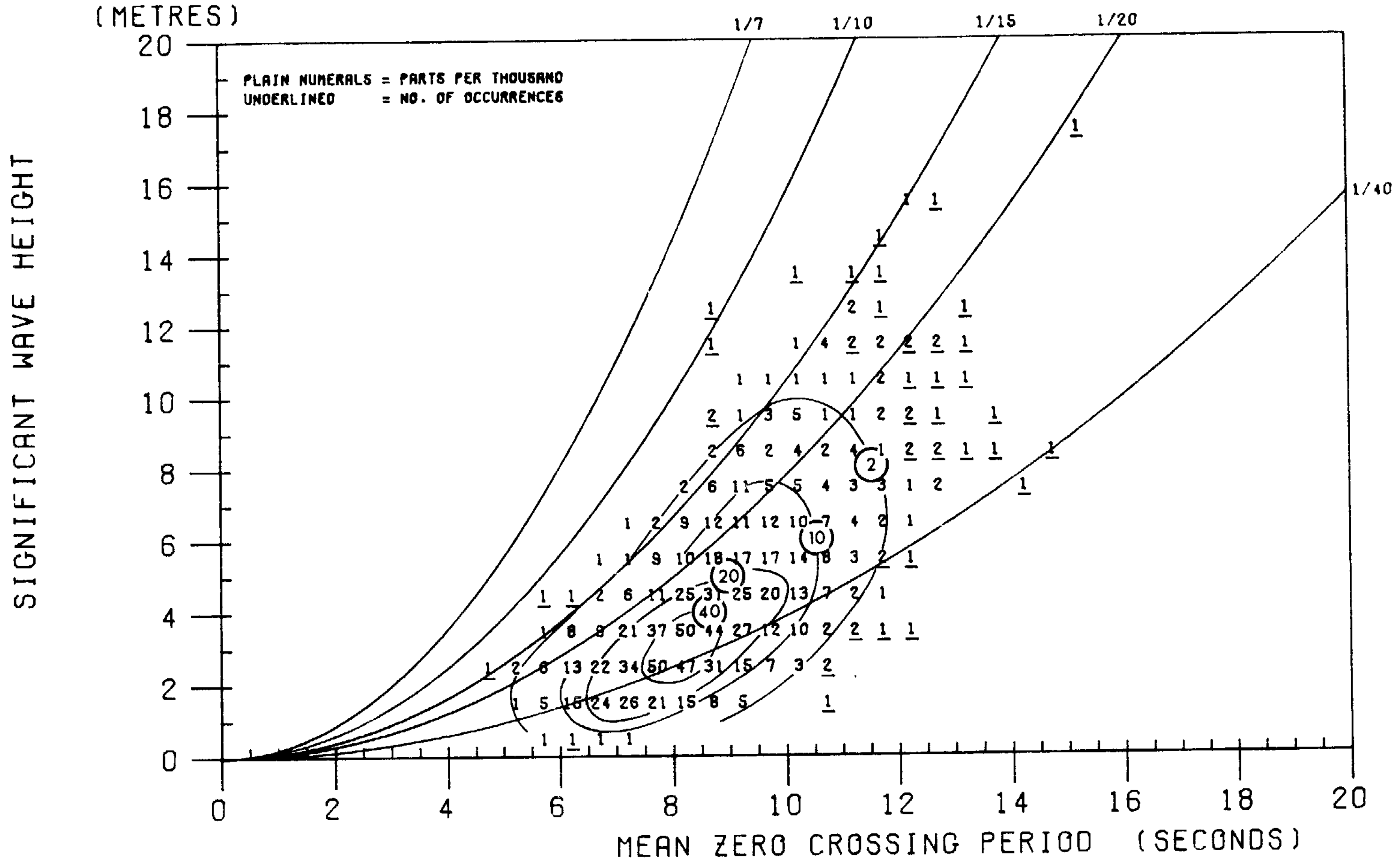

I2
PERCENTAGE OCCURRENCE
0
5
10
15
20
25
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
O.W.S. INDIA2
FULL YEAR
CALMS = 0. %

Fig. 10

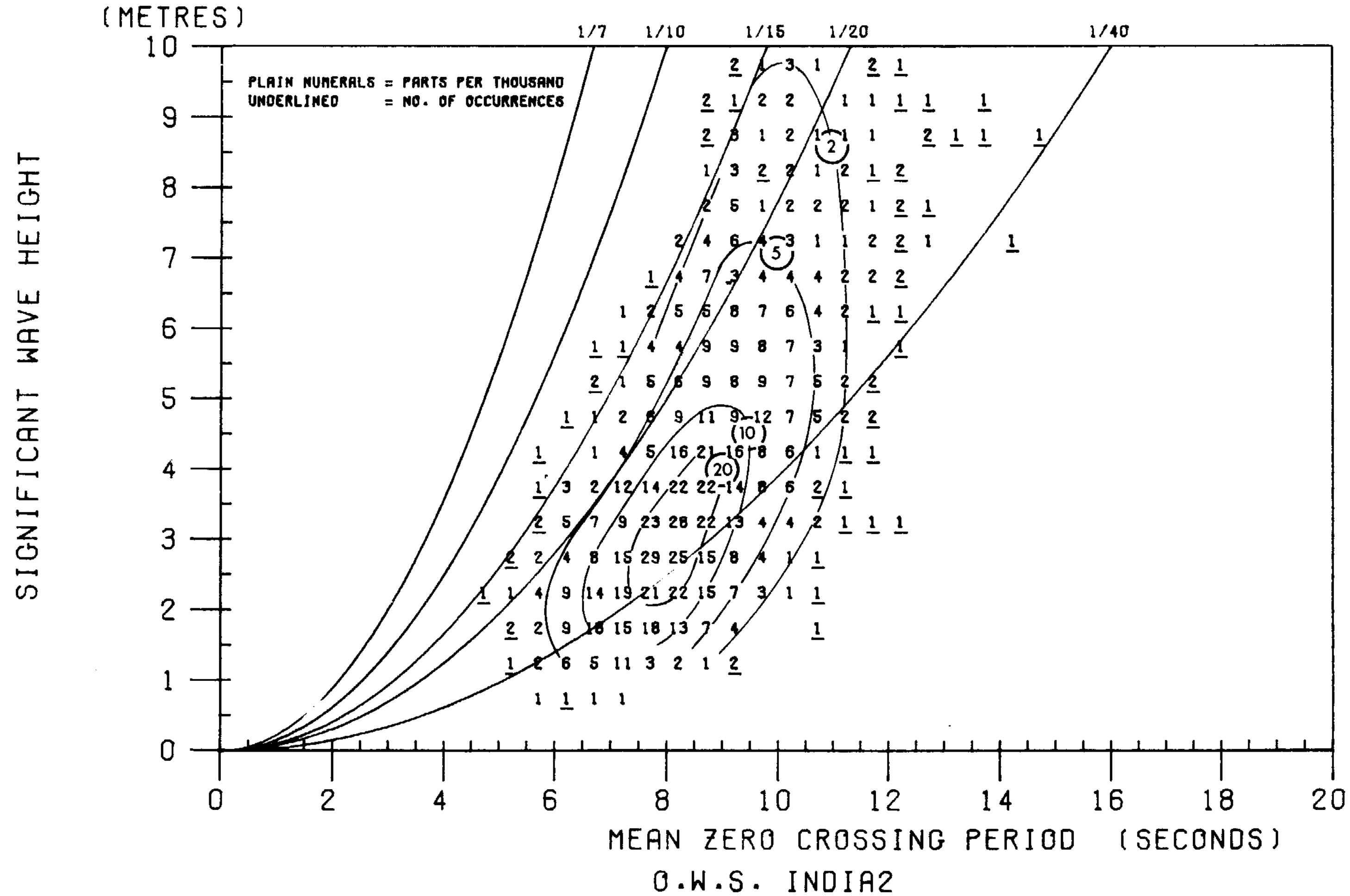


I2

O.W.S. INDIA2

NUMBER OF RECORDS = 2844
CALMS = 0. %
0 VALUES WERE OUTSIDE RANGE

Fig. 11

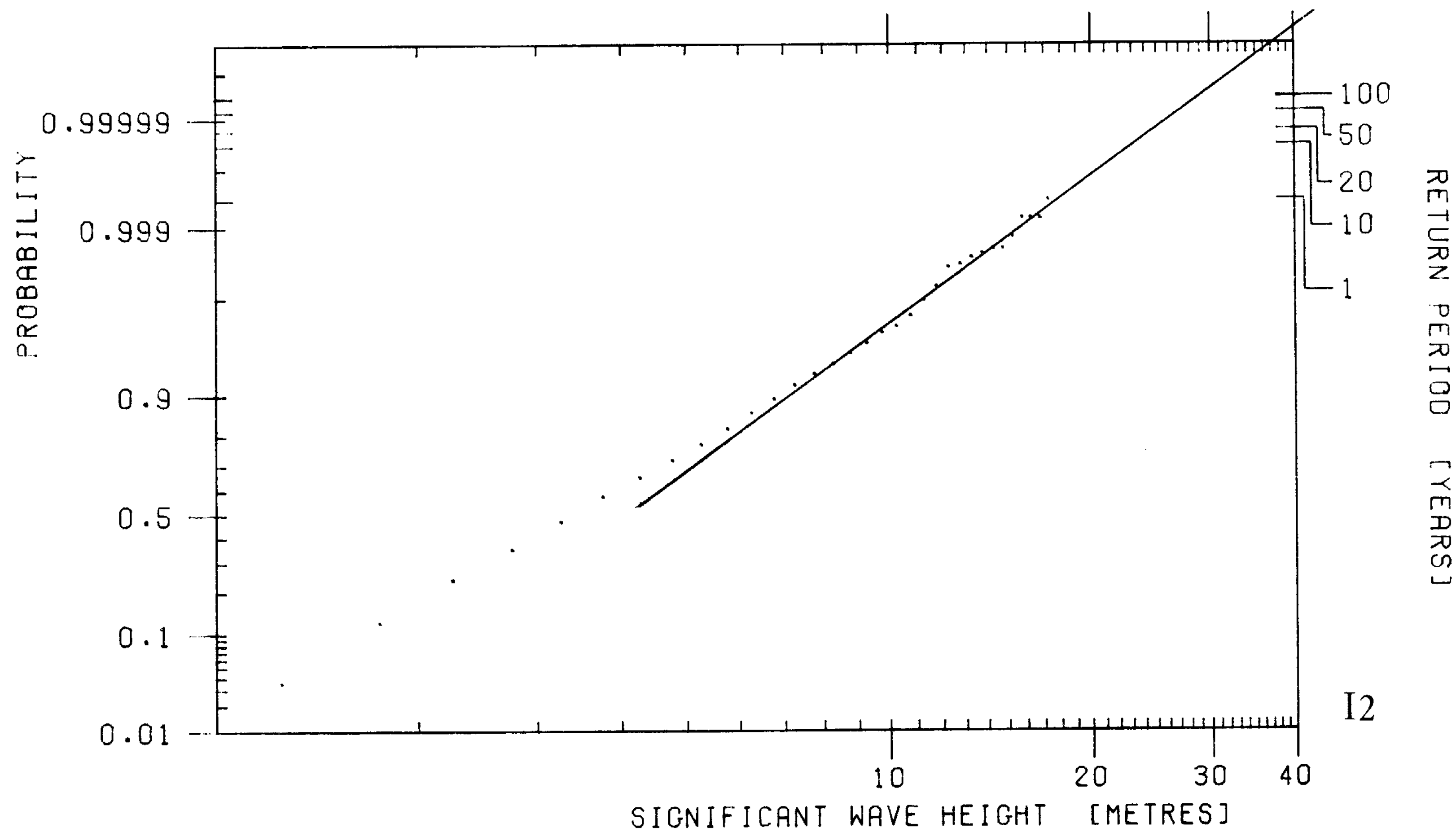


I2

NUMBER OF RECORDS = 2844
CALMS = 0. %
70 VALUES WERE OUTSIDE RANGE

Fig. 12

MIAS



O.W.S. INDIA2

CALMS = 0. %

CUMULATIVE PROBABILITY PLOT - LOG-NORMAL SCALE

Fig. 13

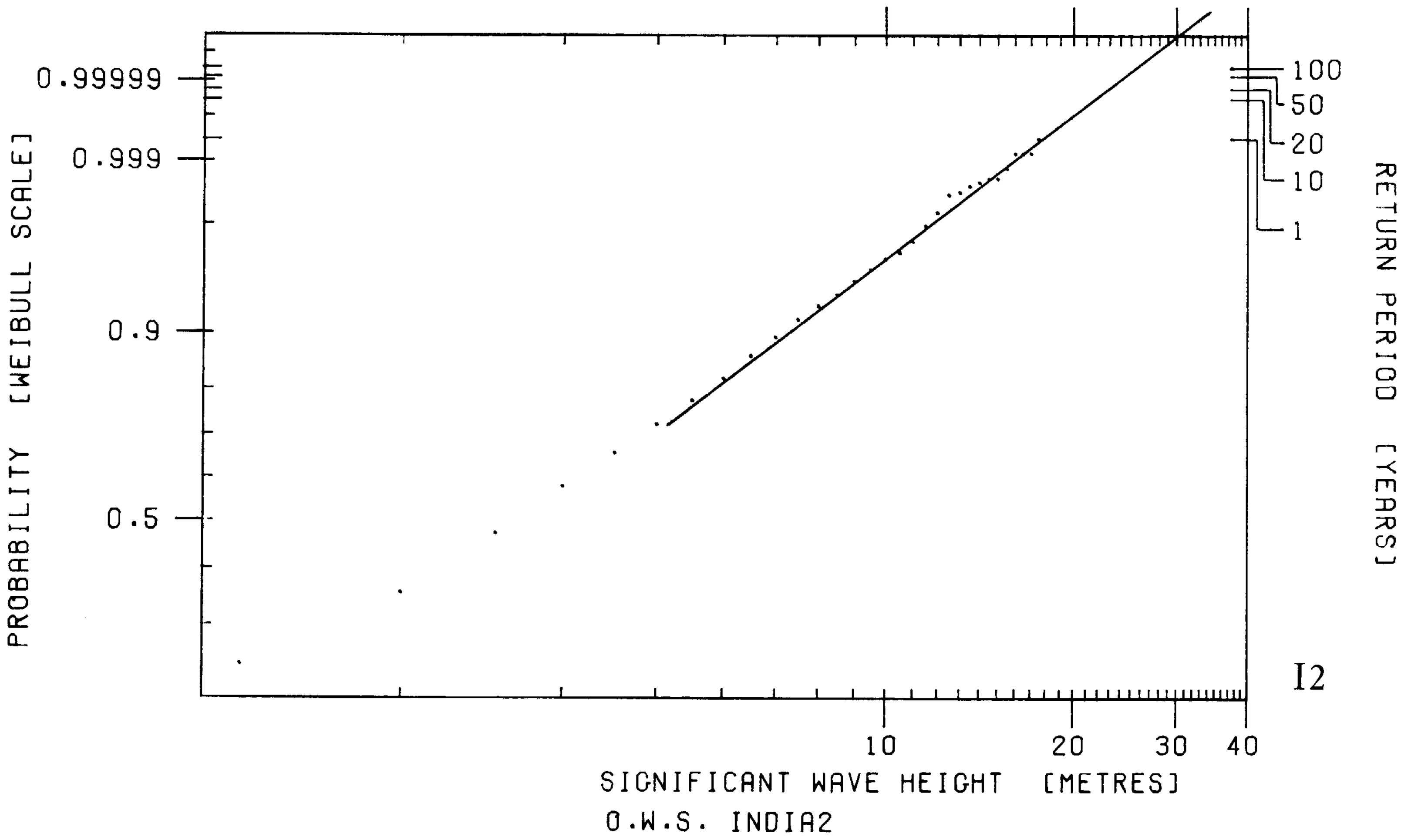

PROBABILITY [WEIBULL SCALE]
0.99999
0.999
0.9
0.5
RETURN PERIOD [YEARS]
100
50
20
10
1
I2
10
20
30
40
SIGNIFICANT WAVE HEIGHT [METRES]
O.W.S. INDIA2
CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = 2.0

Fig. 14

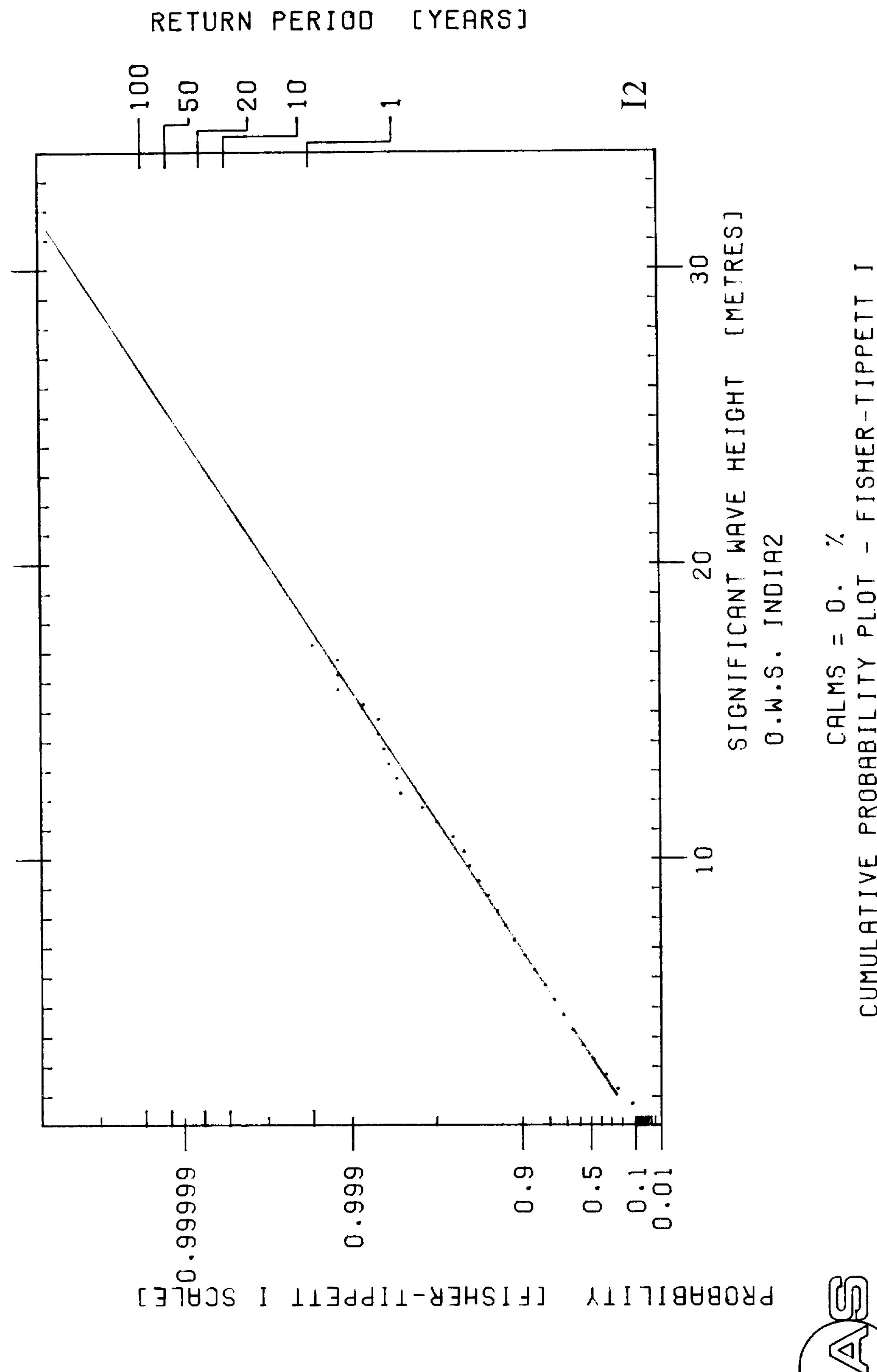
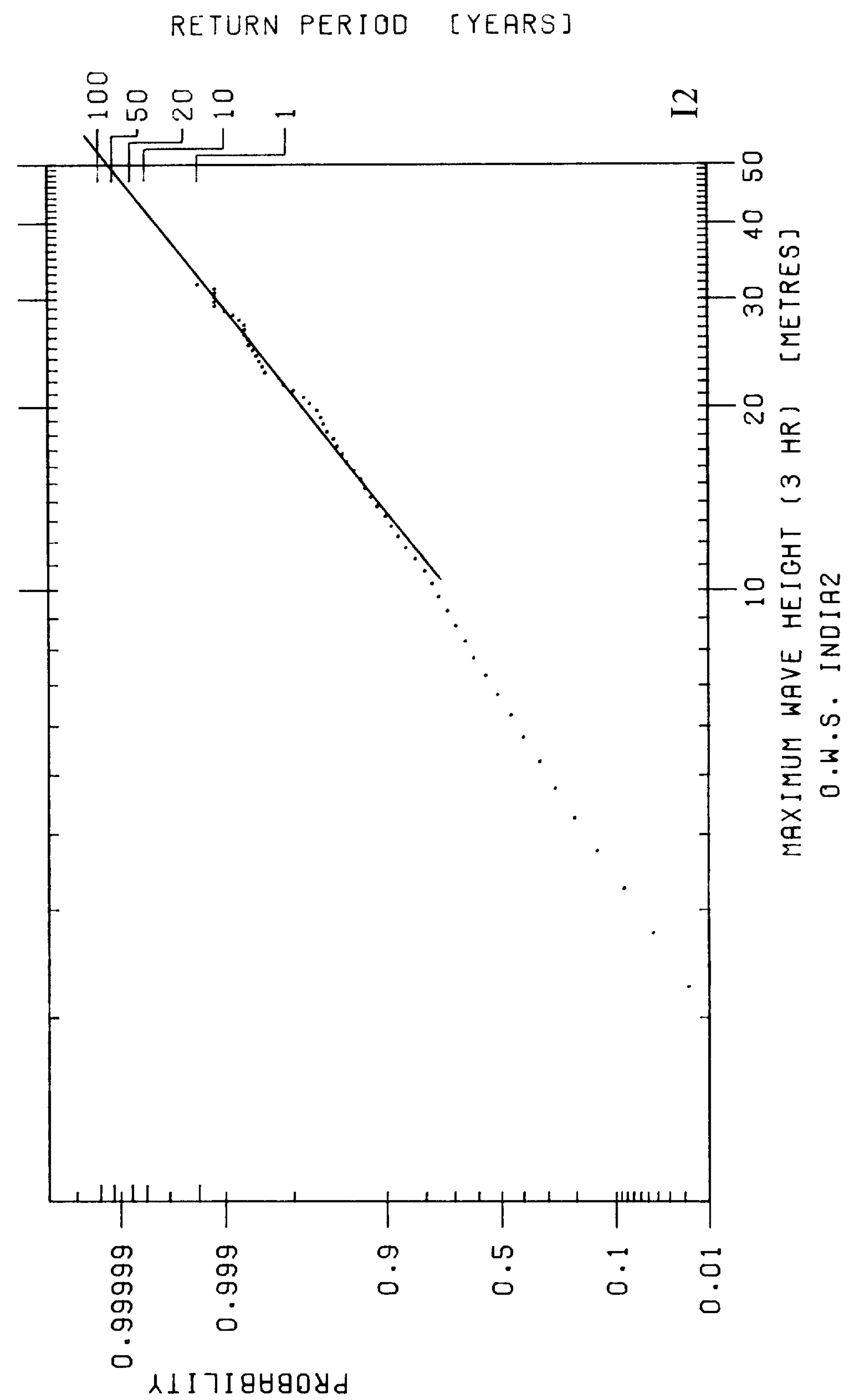

RETURN PERIOD [YEARS]
100
50
20
10
1
I2
PROBABILITY [FISHER-TIPPETT I SCALE]
0.99999
0.999
0.9
0.5
0.1
0.01
10
20
30
SIGNIFICANT WAVE HEIGHT [METRES]
O.W.S. INDIA2
CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - FISHER-TIPPETT I

Fig.15



CALMS = 0. %

CUMULATIVE PROBABILITY PLOT - LOG-NORMAL SCALE

Fig. 16

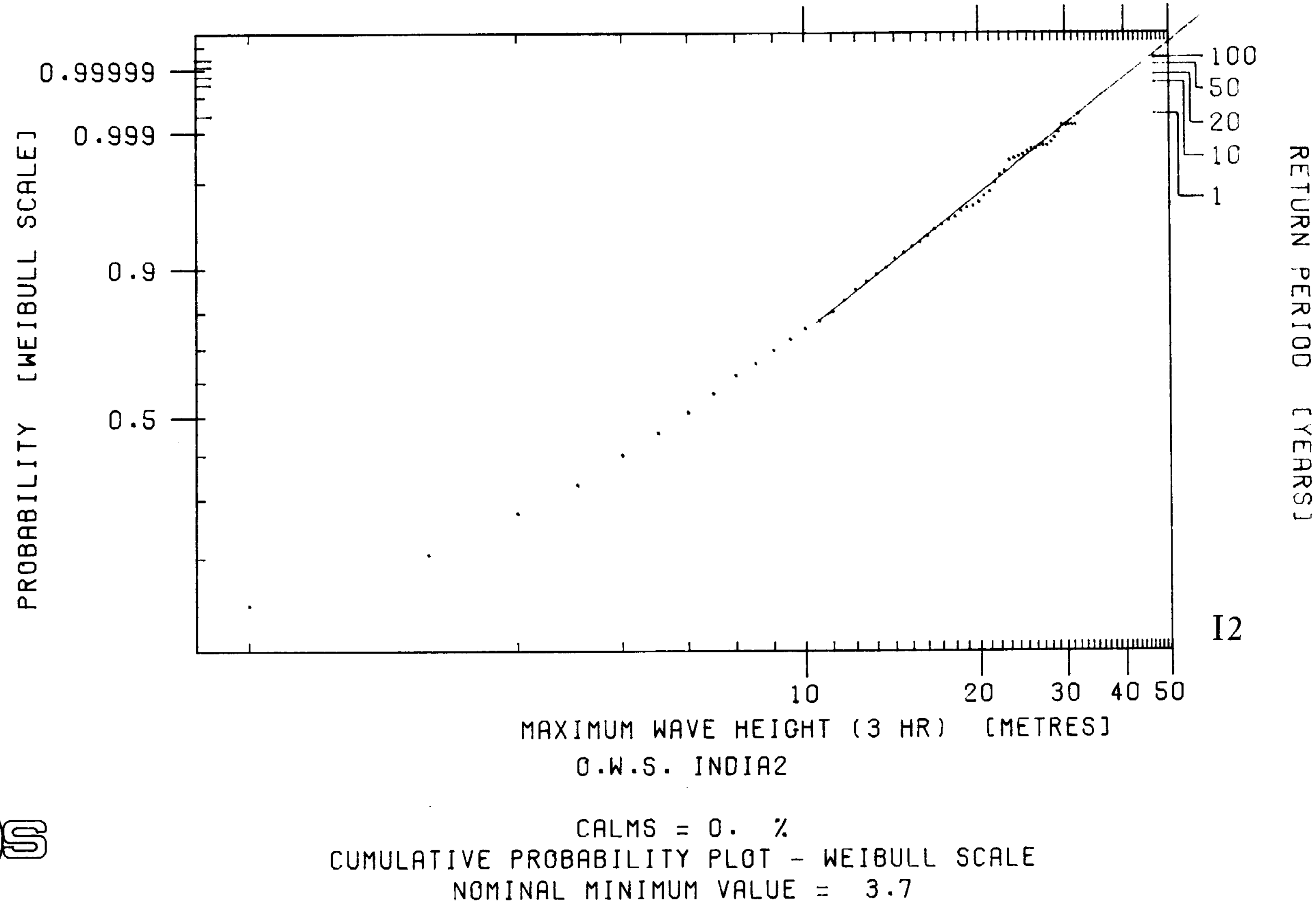

PROBABILITY [WEIBULL SCALE]
0.99999
0.999
0.9
0.5
RETURN PERIOD [YEARS]
100
50
20
10
1
I2
10
20
30
40
50
MAXIMUM WAVE HEIGHT (3 HR) [METRES]
O.W.S. INDIA2
CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = 3.7

Fig. 17

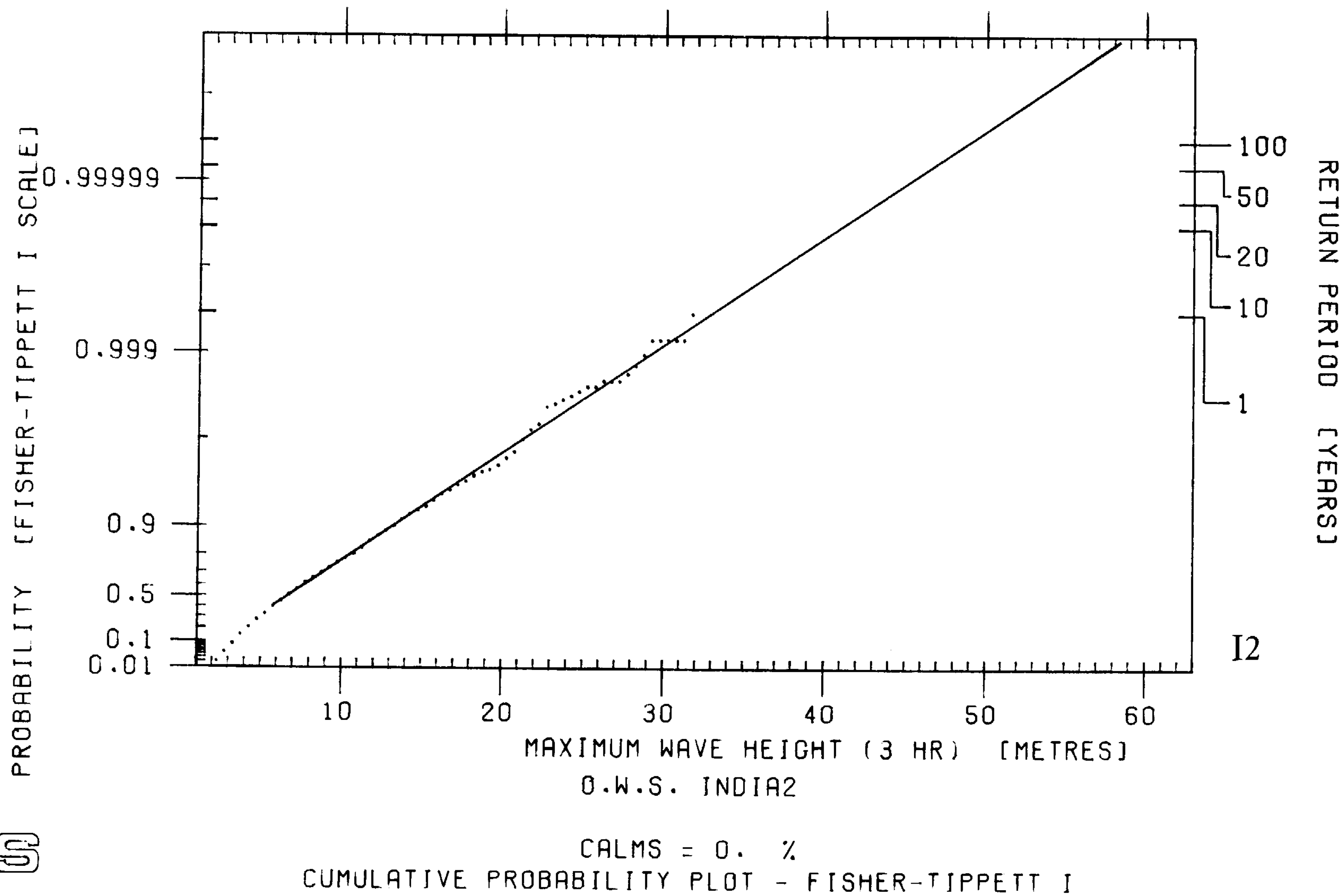
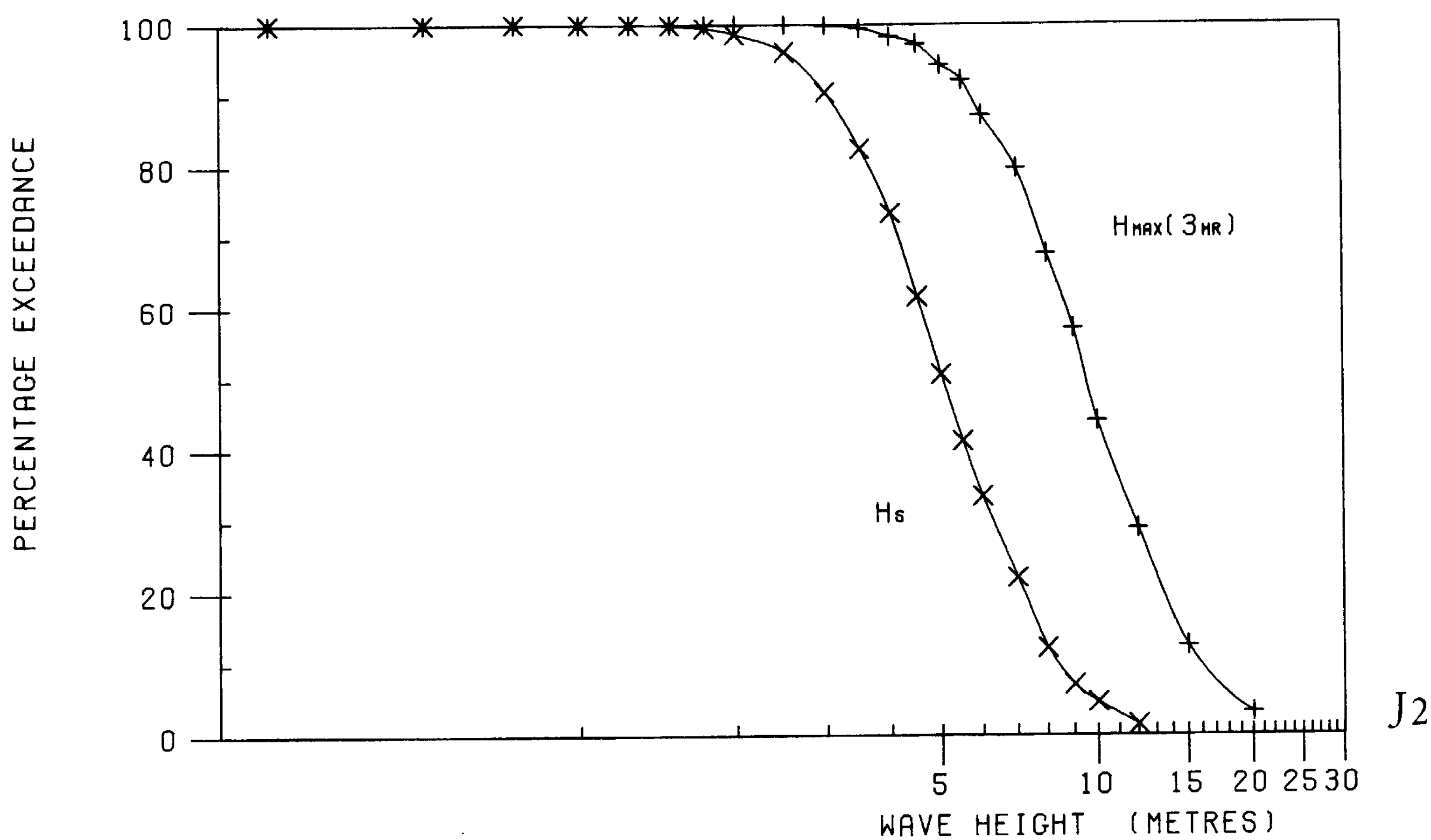

PROBABILITY [FISHER-TIPPETT I SCALE]
0.99999
0.999
0.9
0.5
0.1
0.01
RETURN PERIOD [YEARS]
100
50
20
10
1
I2
10
20
30
40
50
60
MAXIMUM WAVE HEIGHT (3 HR) [METRES]
O.W.S. INDIA2
CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - FISHER-TIPPETT I

Fig. 18



O.W.S. JULIETT2
WINTER (JANUARY TO MARCH)
CALMS = 0. %

Fig. 19

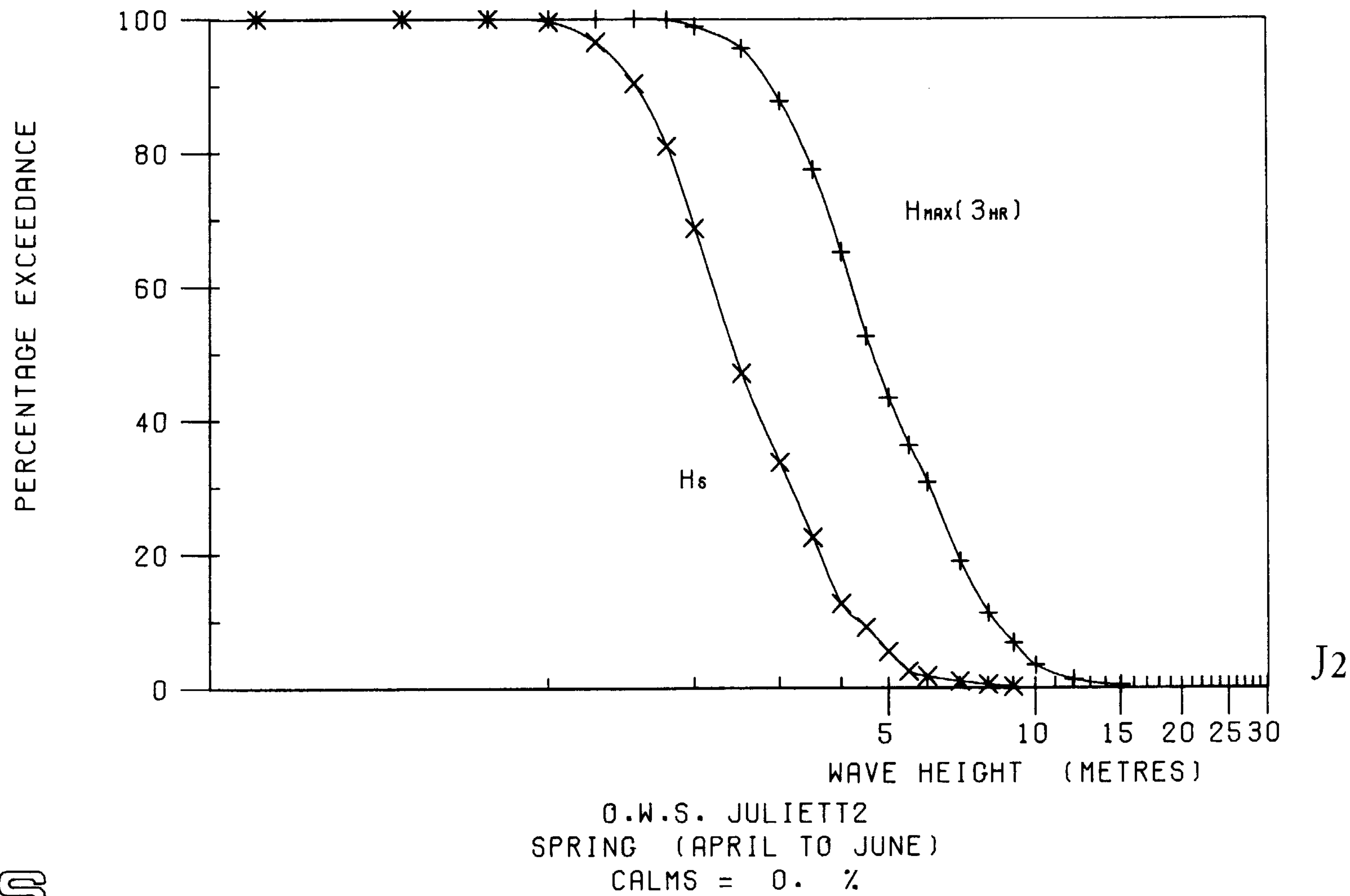
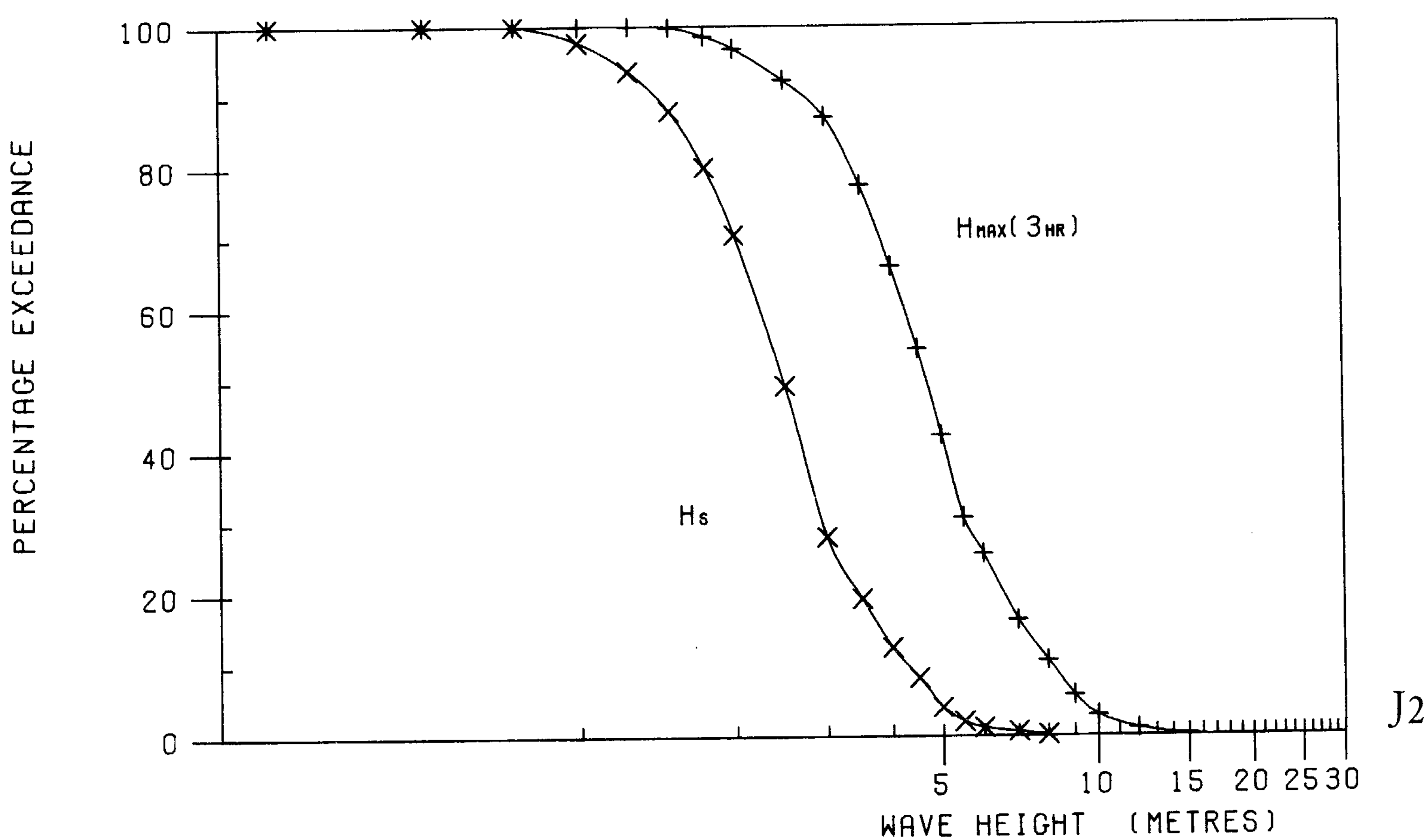

100
80
60
40
20
0
PERCENTAGE EXCEEDANCE
Hmax(3hr)
Hs
J2
5
10
15
20
25
30
WAVE HEIGHT (METRES)
O.W.S. JULIETT2
SPRING (APRIL TO JUNE)
CALMS = 0. %

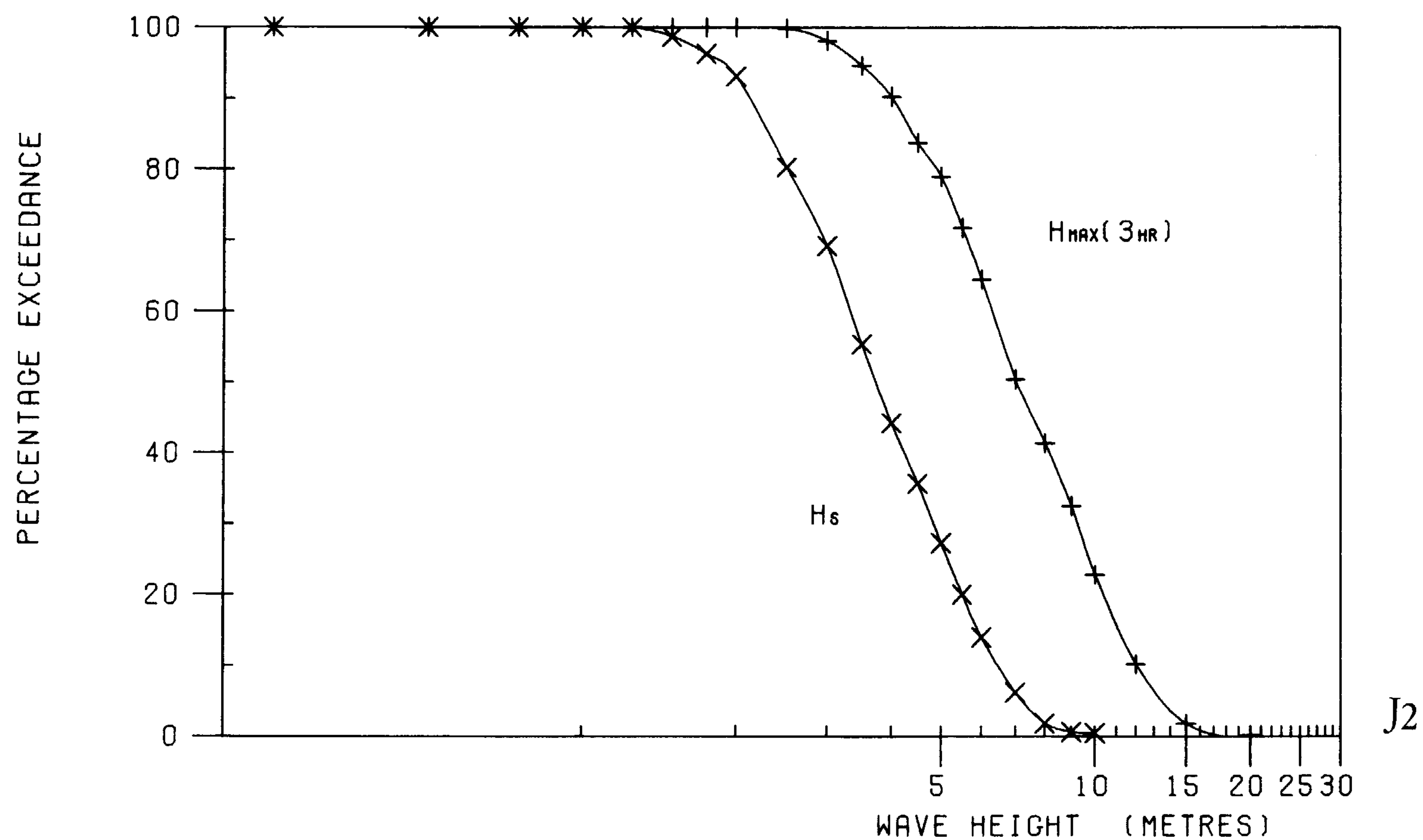
Fig. 20



O.W.S. JULIETT2
SUMMER (JULY TO SEPTEMBER)
CALMS = 0. %

MIAS

Fig. 21



O.W.S. JULIETT2
AUTUMN (OCTOBER TO DECEMBER)
CALMS = 0. %

Fig. 22

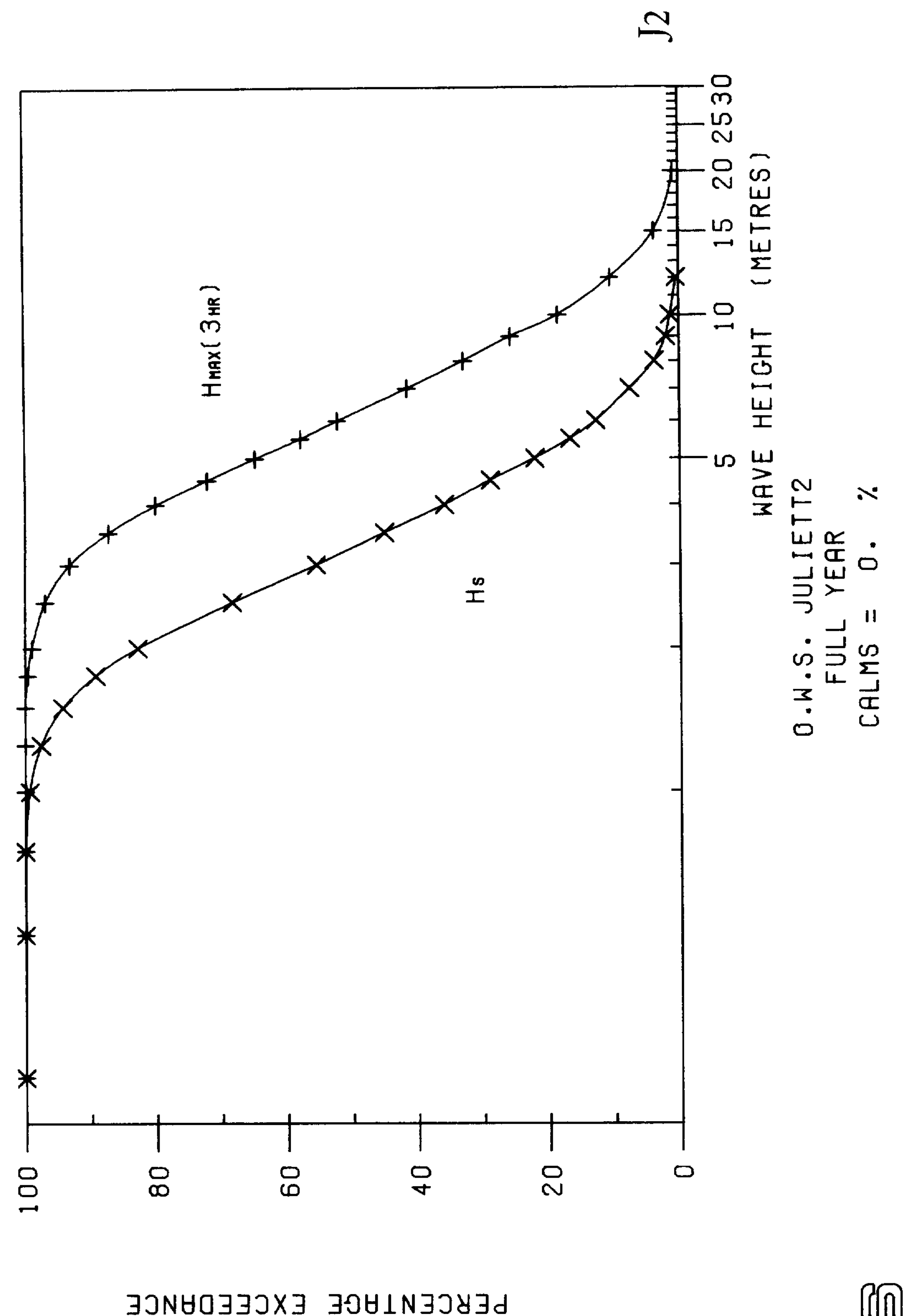
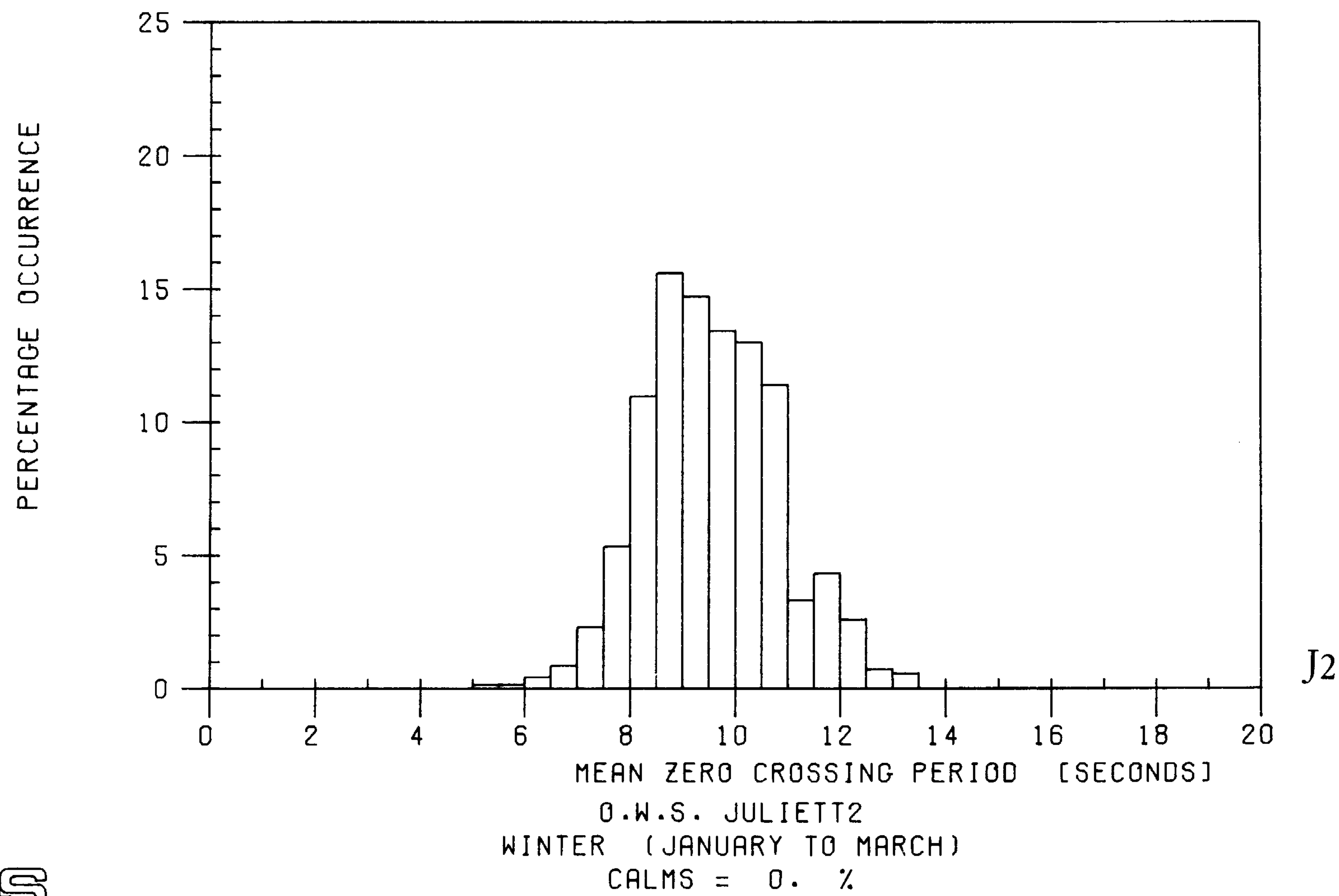

J2
PERCENTAGE EXCEEDANCE
100
80
60
40
20
0
5
10
15
20
25
30
WAVE HEIGHT (METRES)
HMAX(3HR)
Hs
O.W.S. JULIETT2
FULL YEAR
CALMS = 0. %

Fig.23


PERCENTAGE OCCURRENCE
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
J2
MEAN ZERO CROSSING PERIOD [SECONDS]
O.W.S. JULIETT2
WINTER (JANUARY TO MARCH)
CALMS = 0. %

MIAS

Fig. 24

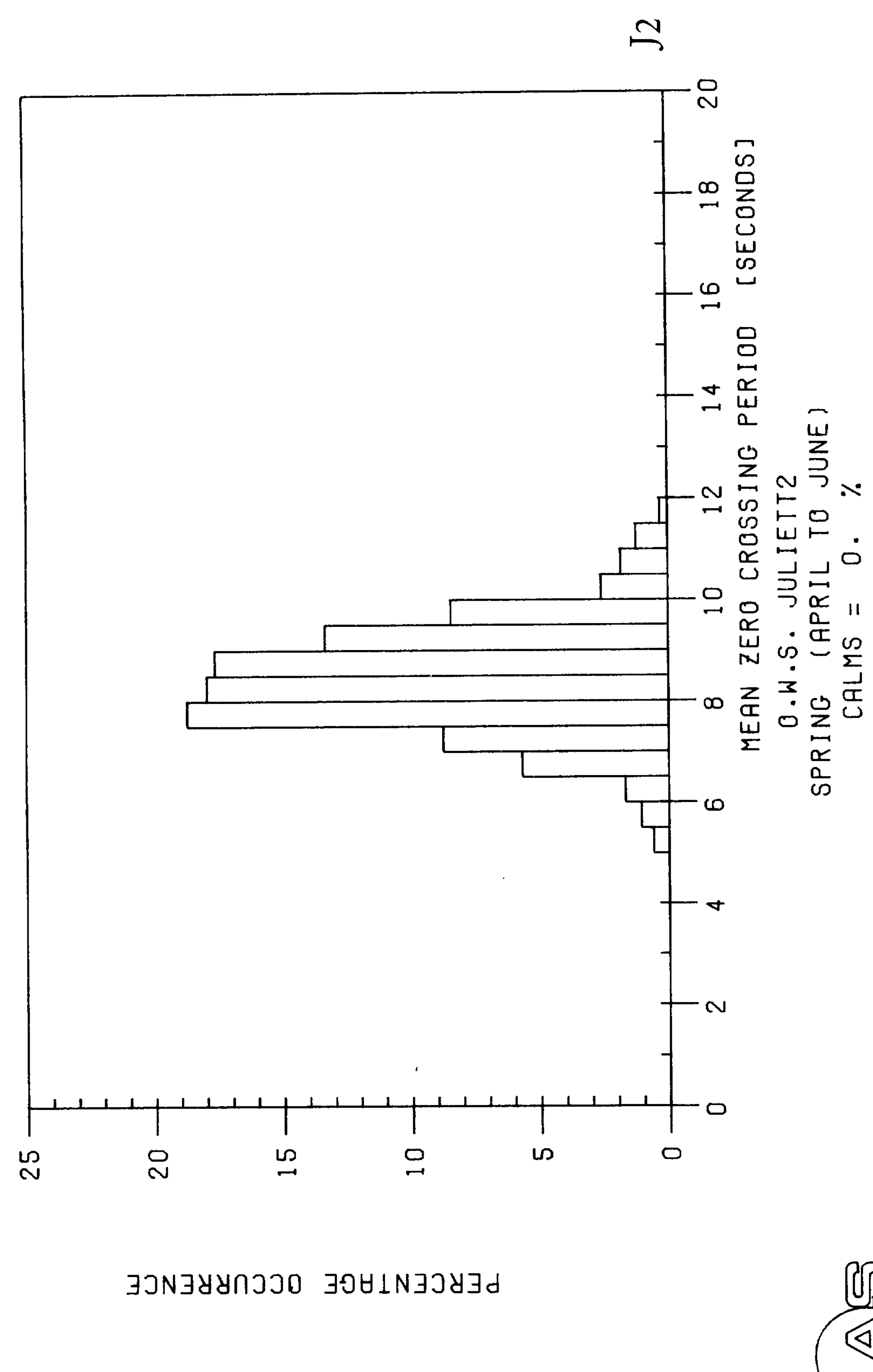

J2
PERCENTAGE OCCURRENCE
0
5
10
15
20
25
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
O.W.S. JULIETT2
SPRING (APRIL TO JUNE)
CALMS = 0. %

Fig. 25

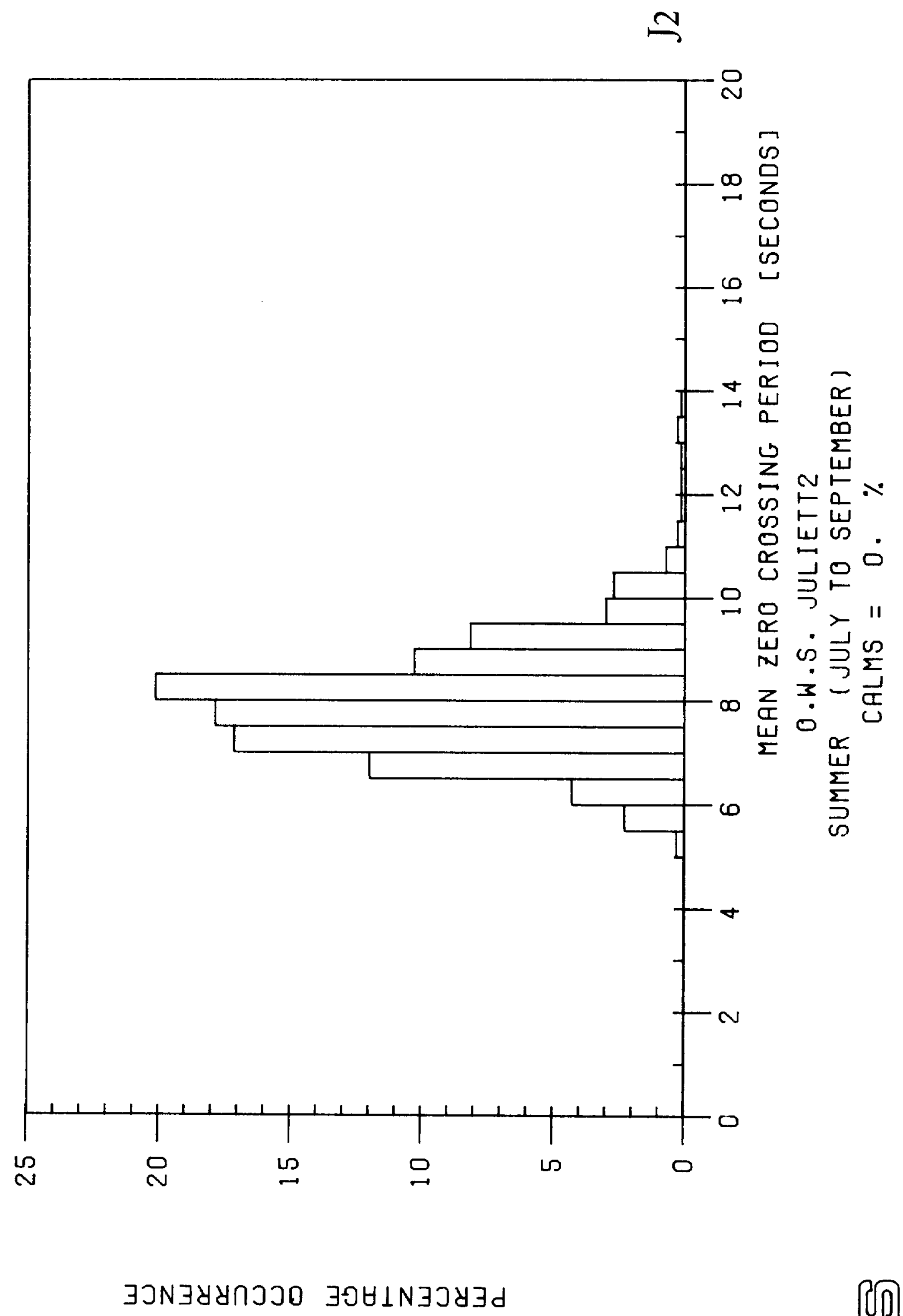

J2
PERCENTAGE OCCURRENCE
0
5
10
15
20
25
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
O.W.S. JULIETT2
SUMMER (JULY TO SEPTEMBER)
CALMS = 0. %

Fig. 26

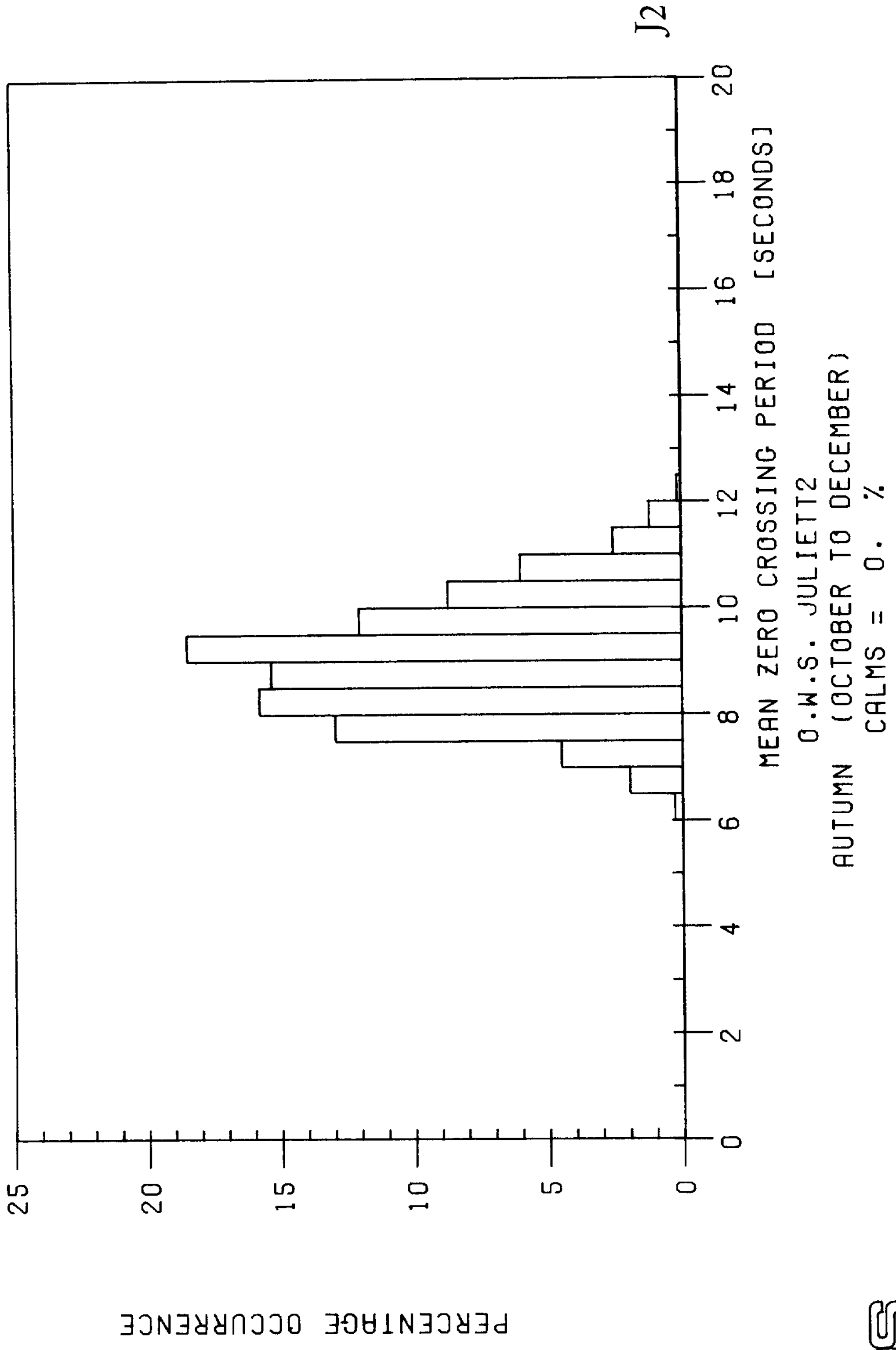

J2
PERCENTAGE OCCURRENCE
0
5
10
15
20
25
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
O.W.S. JULIETT2
AUTUMN (OCTOBER TO DECEMBER)
CALMS = 0. %

Fig. 27

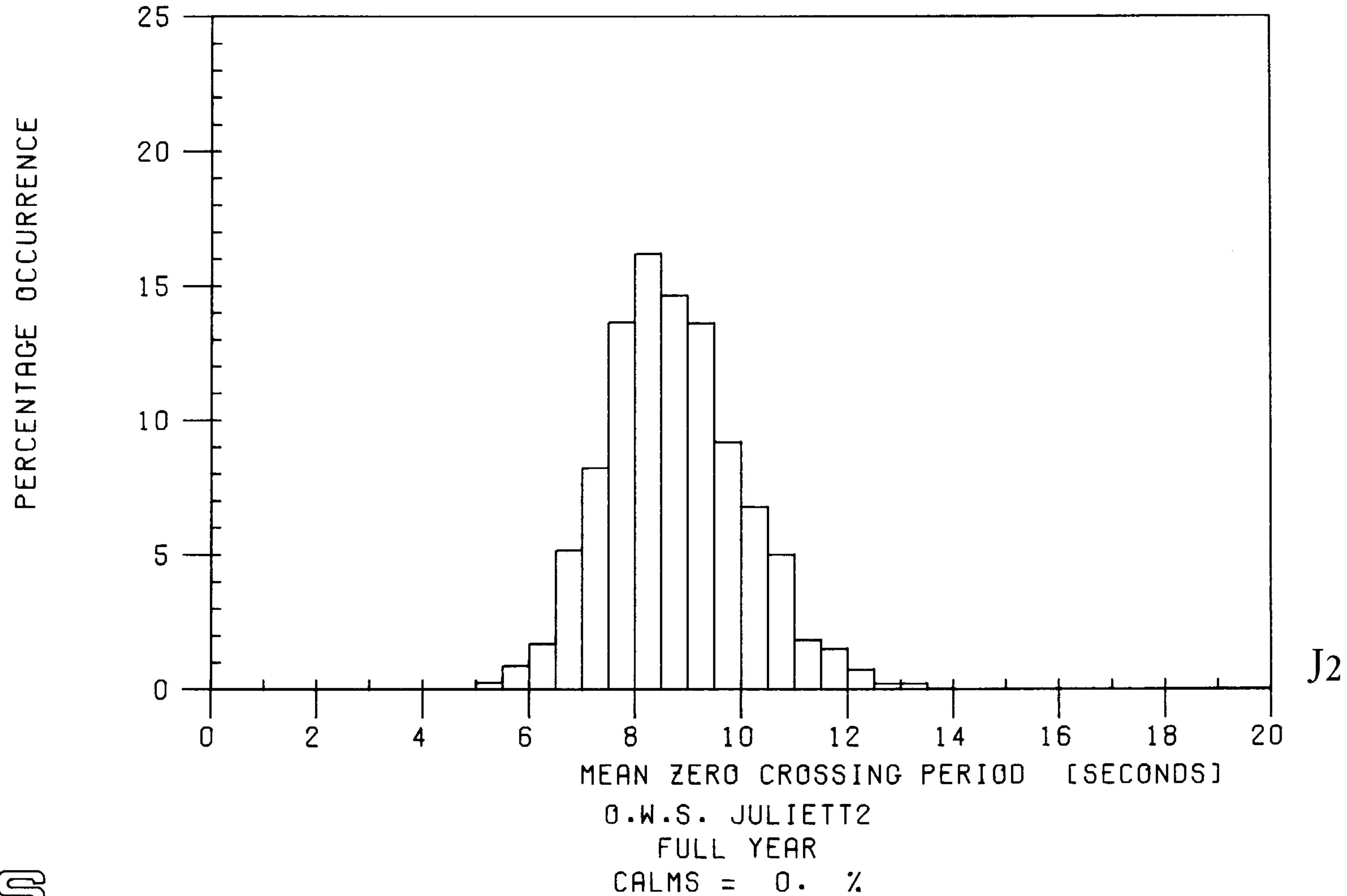
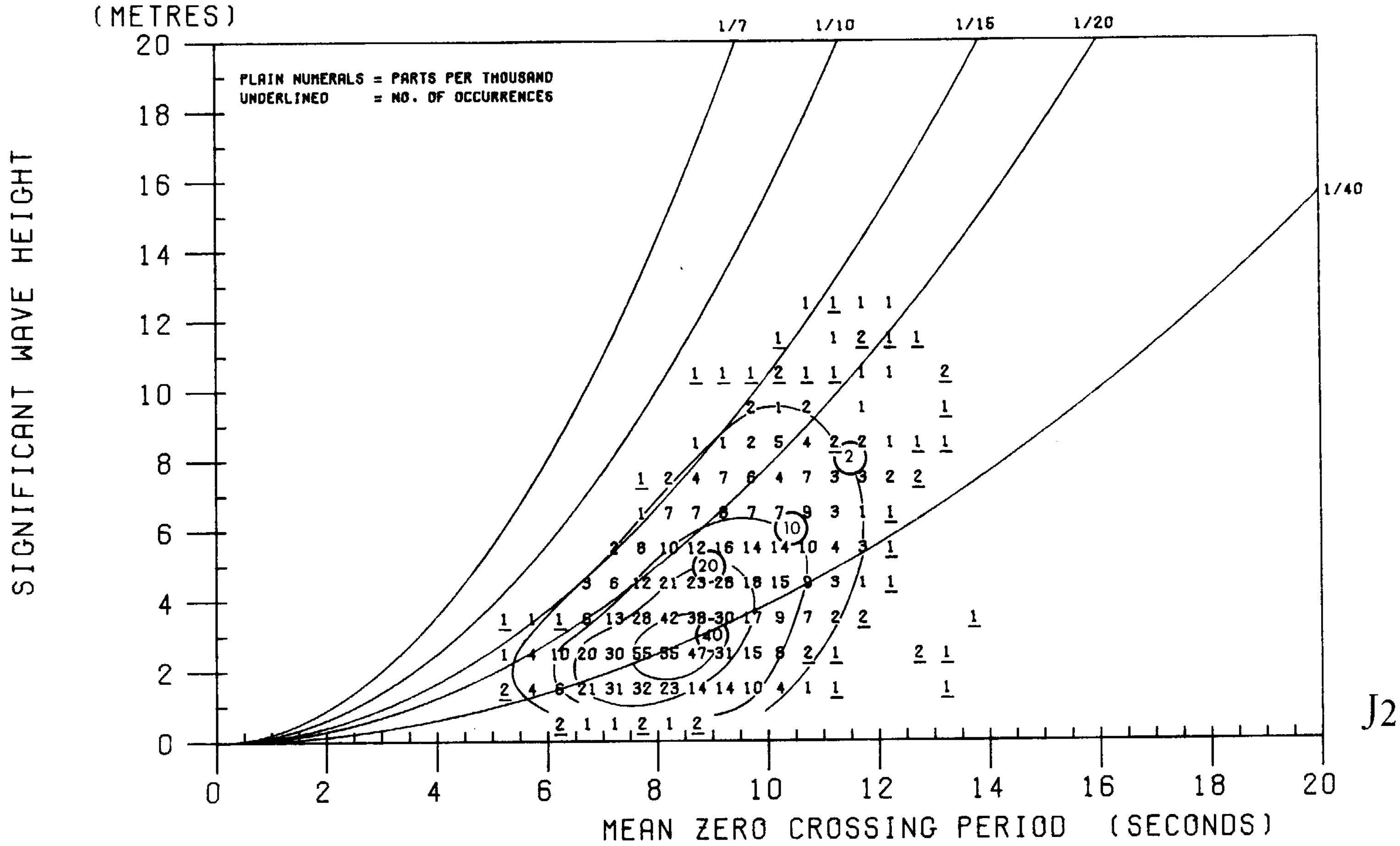

25
20
15
10
5
0
PERCENTAGE OCCURRENCE
0
2
4
6
8
10
12
14
16
18
20
MEAN ZERO CROSSING PERIOD [SECONDS]
O.W.S. JULIETT2
FULL YEAR
CALMS = 0. %
J2

Fig. 28



O.W.S. JULIETT2

NUMBER OF RECORDS = 2708
CALMS = 0. %
0 VALUES WERE OUTSIDE RANGE

Fig. 29

MIAS

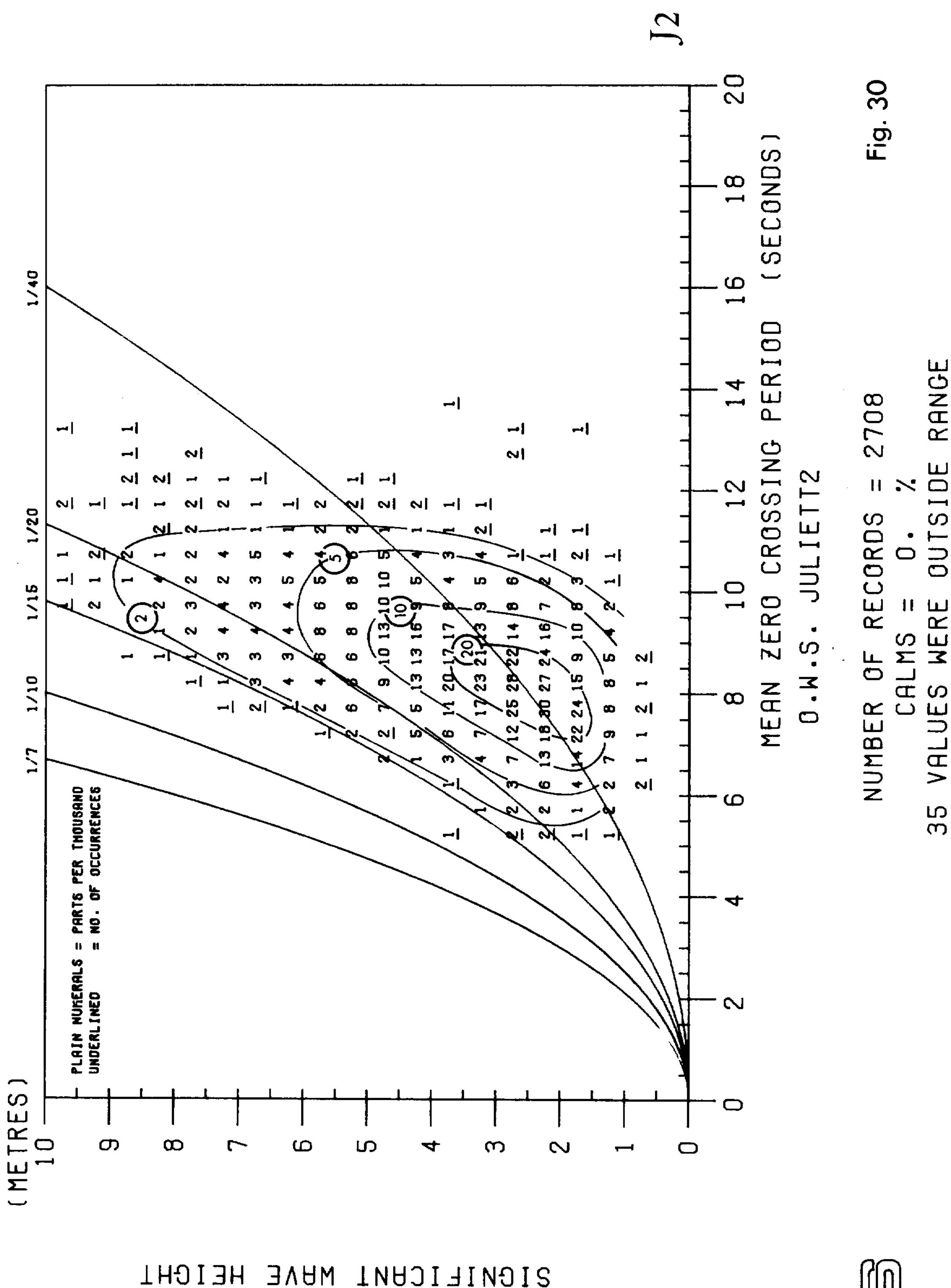
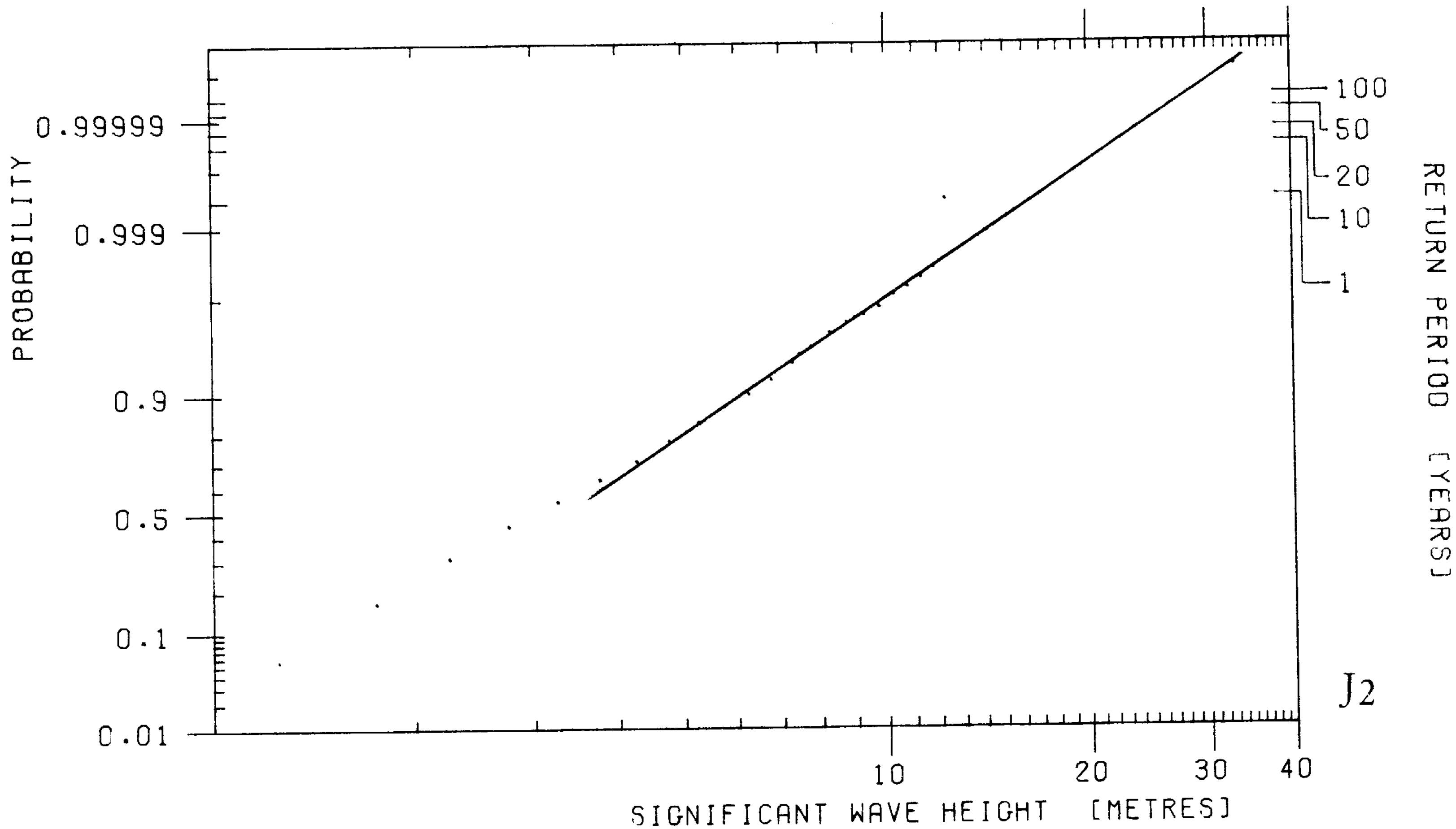

J2
SIGNIFICANT WAVE HEIGHT
(METRES)
PLAIN NUMERALS = PARTS PER THOUSAND
UNDERLINED = NO. OF OCCURRENCES
1/7
1/10
1/15
1/20
1/40
MEAN ZERO CROSSING PERIOD (SECONDS)
O.W.S. JULIETT2
NUMBER OF RECORDS = 2708
CALMS = 0. %
35 VALUES WERE OUTSIDE RANGE

Fig. 30

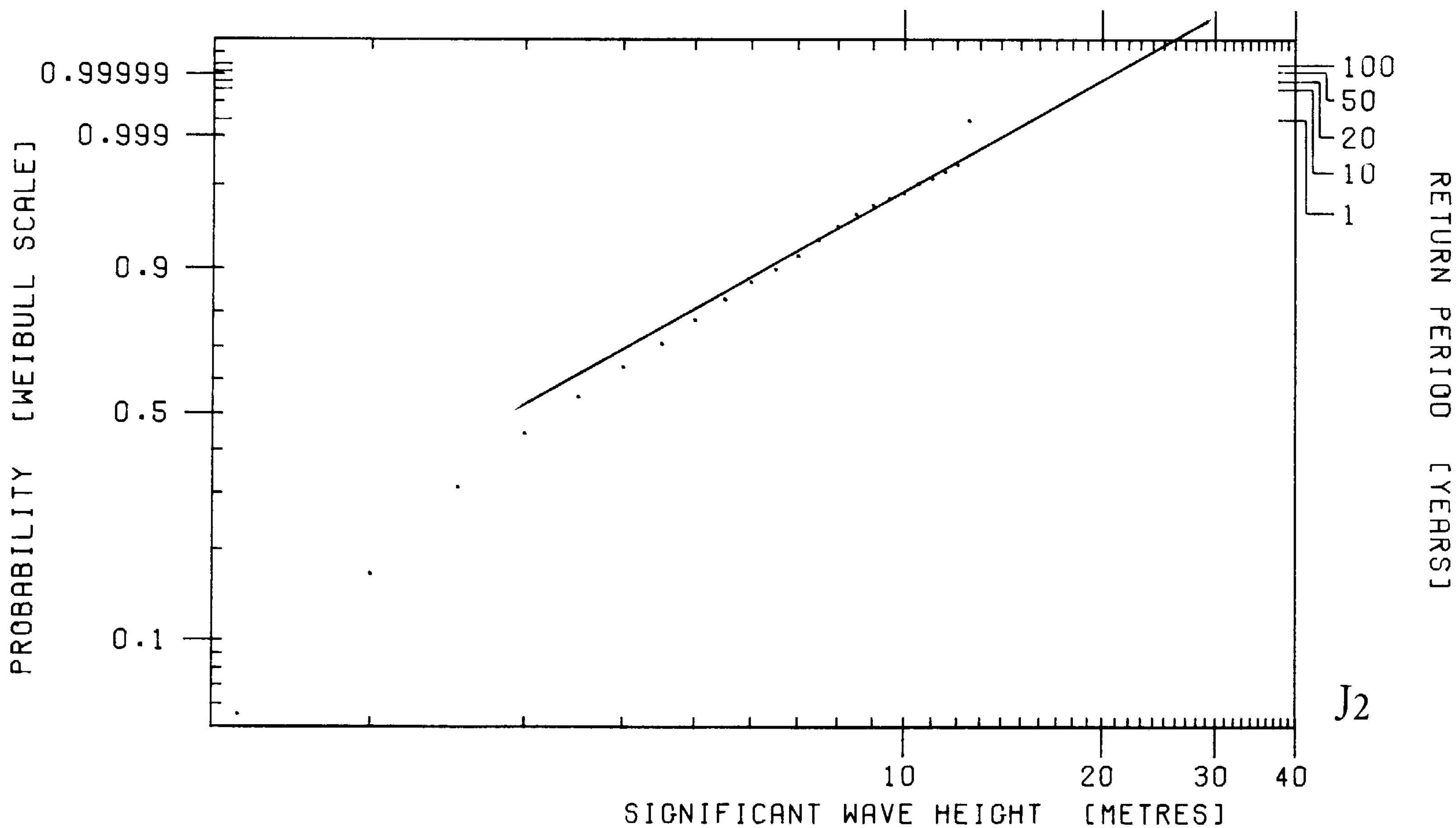


O.W.S. JULIETT2

CALMS = 0. %

CUMULATIVE PROBABILITY PLOT - LOG-NORMAL SCALE

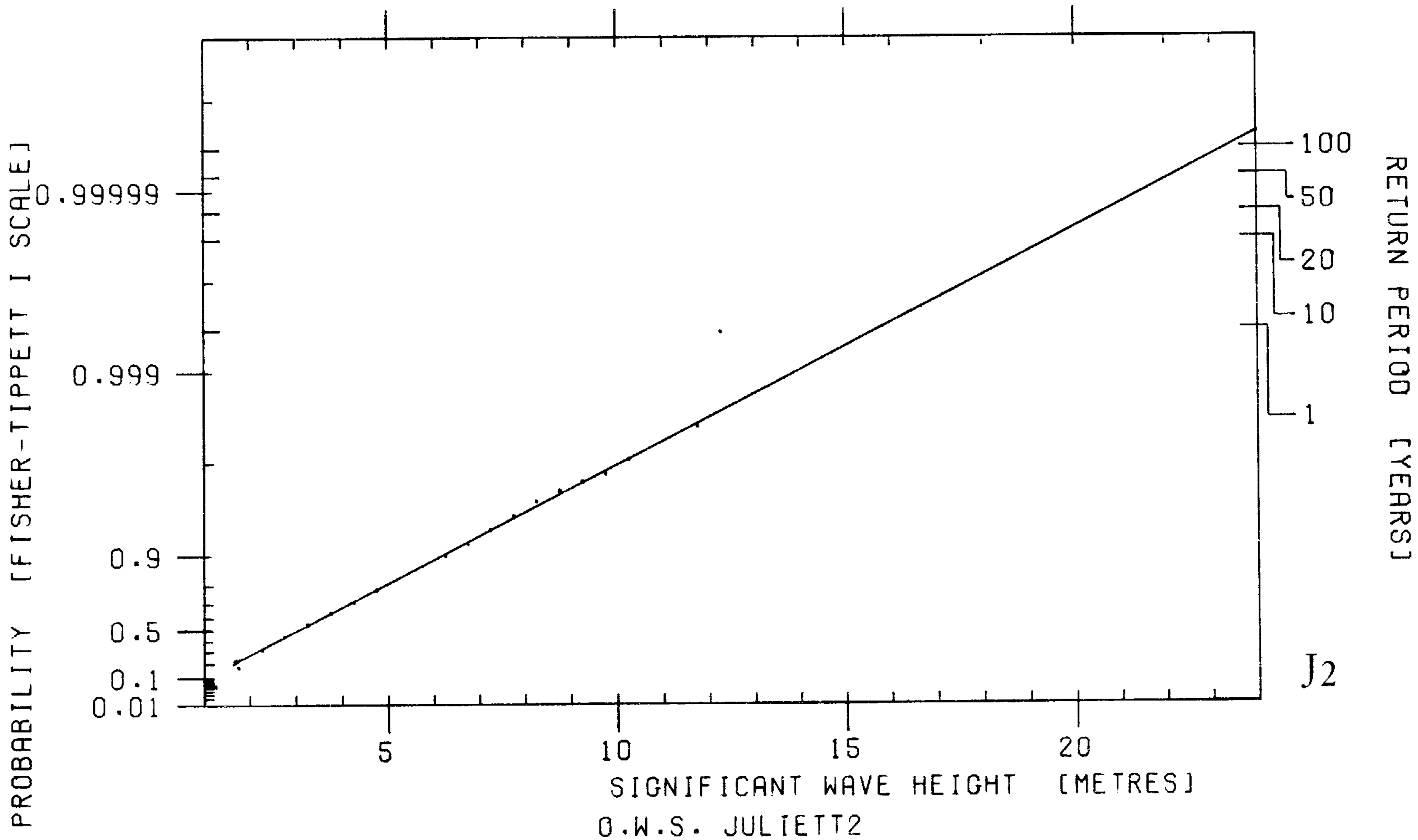
Fig. 31



O.W.S. JULIETT2

CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = 0.7

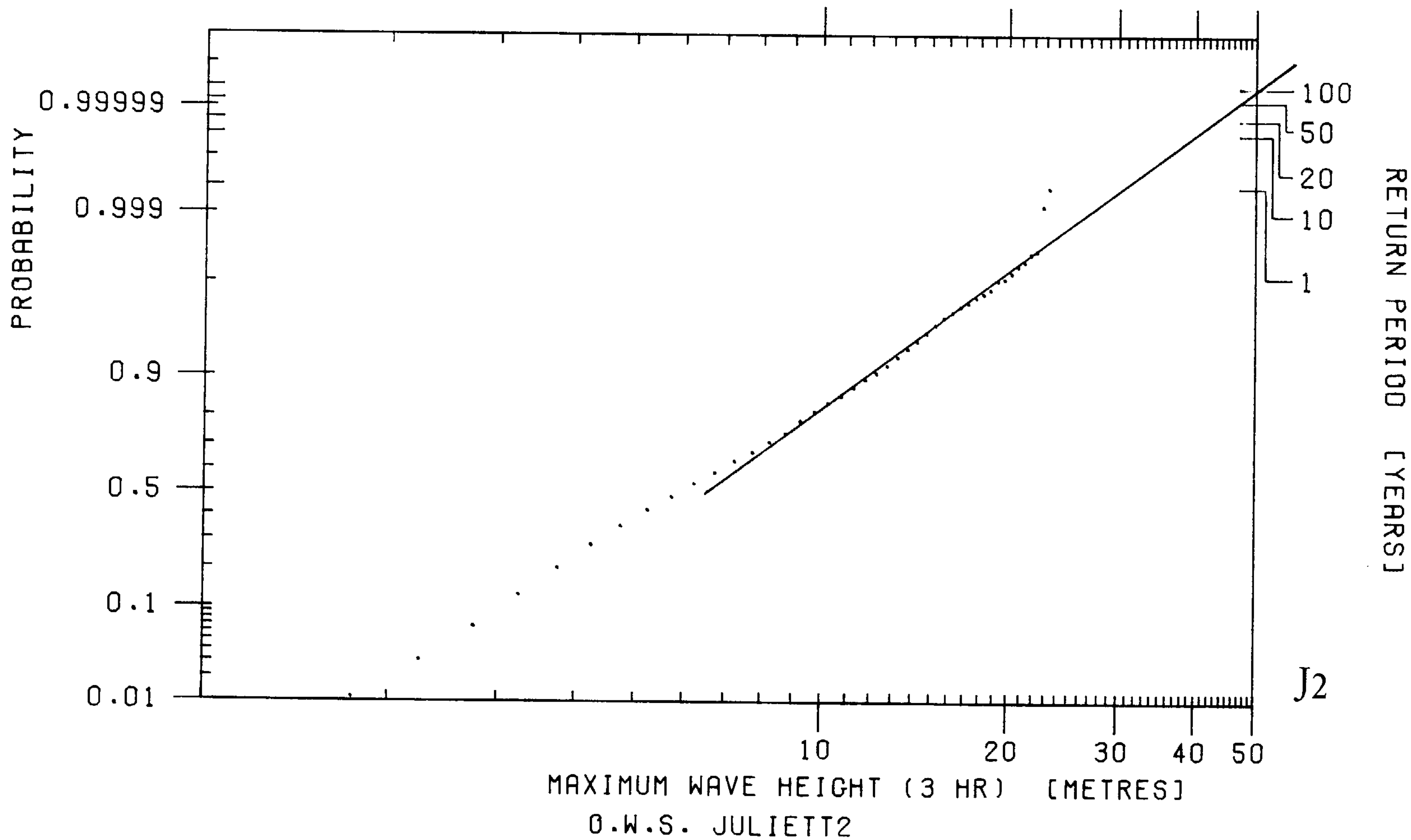
Fig. 32



CALMS = 0. %

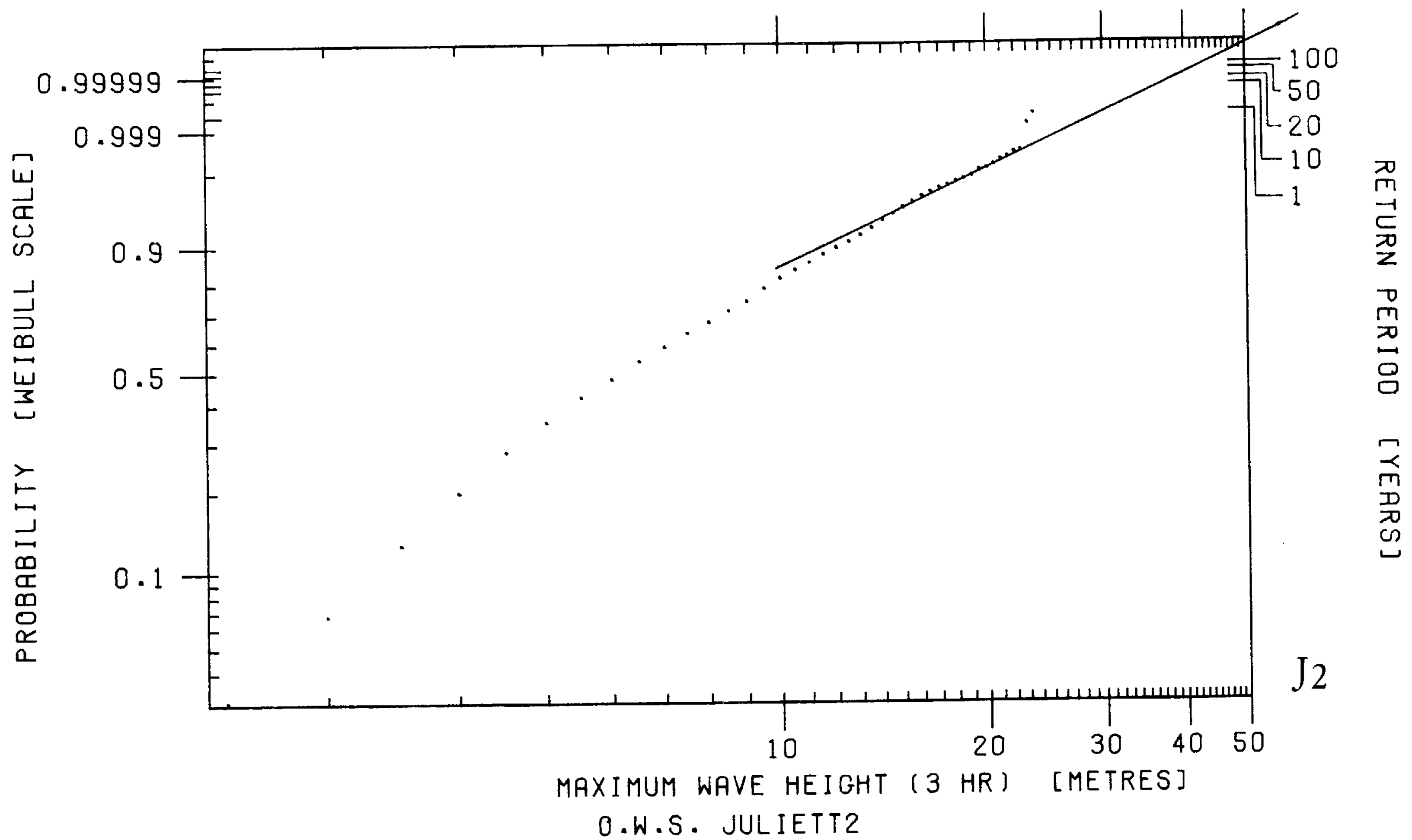
CUMULATIVE PROBABILITY PLOT - FISHER-TIPPETT I

Fig. 33



CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - LOG-NORMAL SCALE

Fig. 34



CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - WEIBULL SCALE
NOMINAL MINIMUM VALUE = 1.4

Fig. 35

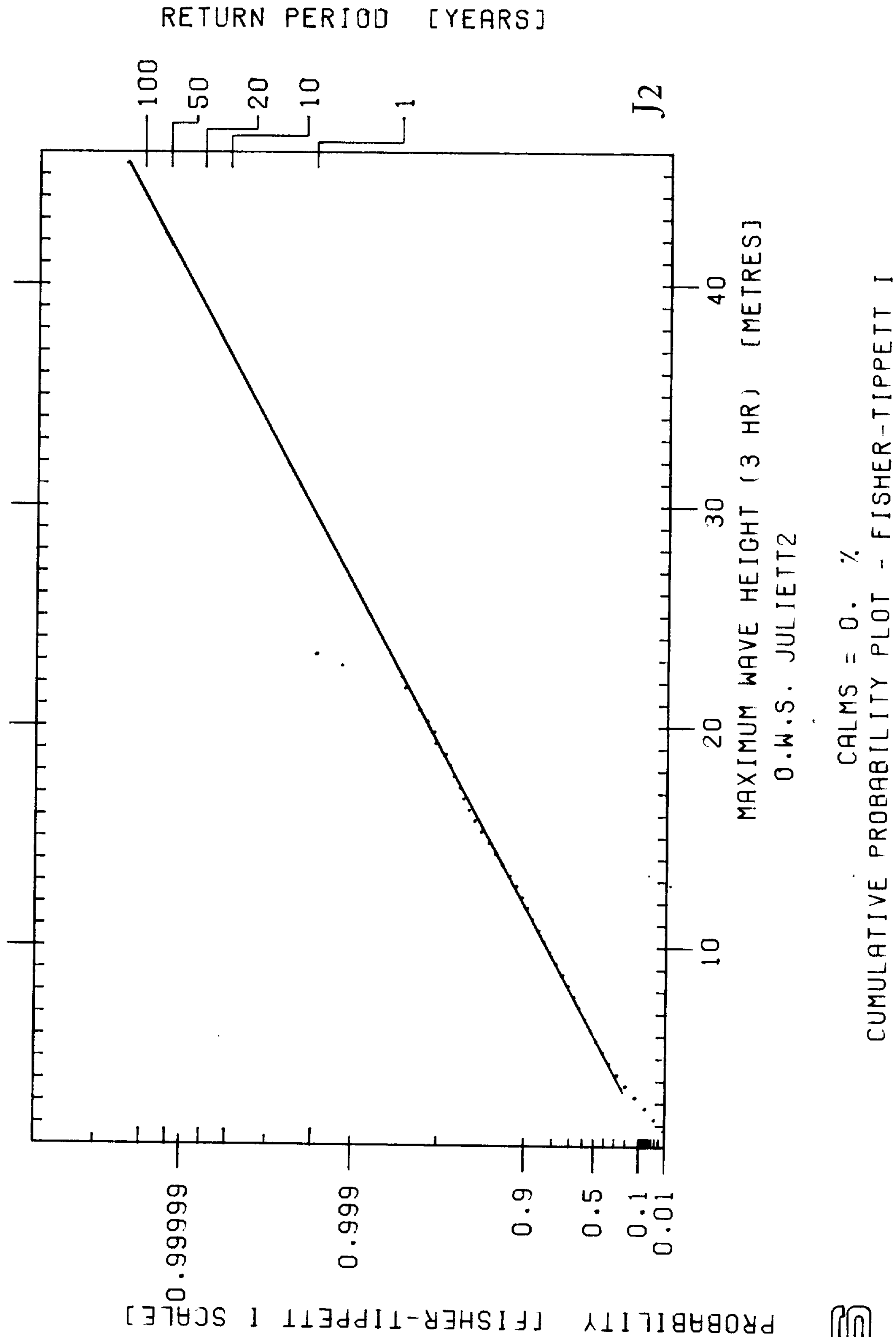
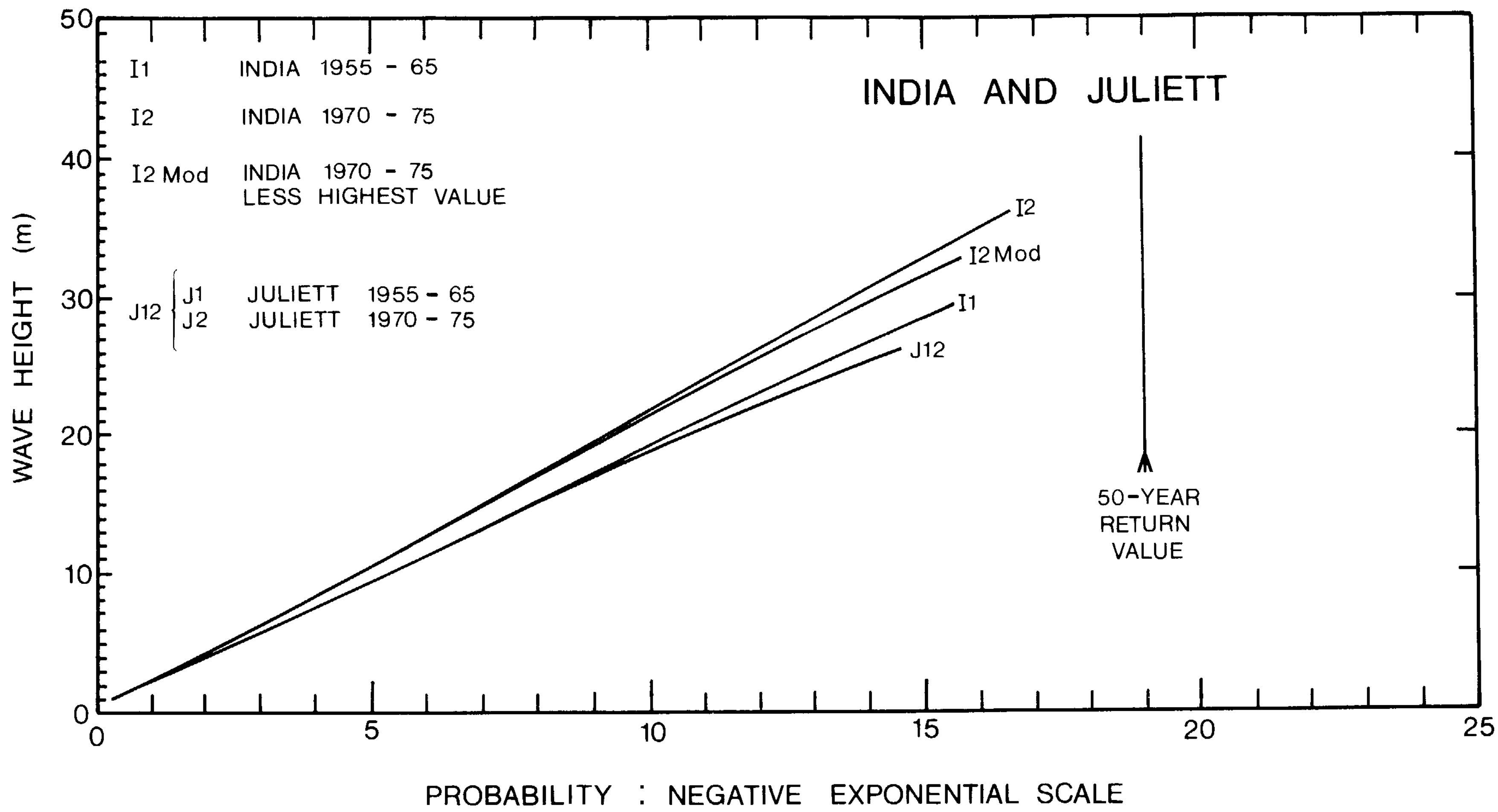

RETURN PERIOD [YEARS]
100
50
20
10
1
J2
MAXIMUM WAVE HEIGHT (3 HR) [METRES]
10
20
30
40
O.W.S. JULIETT2
CALMS = 0. %
CUMULATIVE PROBABILITY PLOT - FISHER-TIPPETT I
PROBABILITY [FISHER-TIPPETT I SCALE]
0.99999
0.999
0.9
0.5
0.1
0.01

Fig. 36



Presentation of data using the Battjes (1972) method. I1 and J1 are the earlier data sets; I2 and J2 are the later data sets. I2 Mod is the INDIA 2 data set without the one highest value. Note that J1 and J2 are indistinguishable on this plot. (Curves have been terminated at twice the highest value of H_s, as recommended by Battjes) **Fig. 37**