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DEACON LABORATORY

WAVES RECORDED AT CHANNEL LIGHT VESSEL 1979–1985

BY

S. BACON

REPORT NO. 263

1989

Natural Environment Research Council

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DOCUMENT DATA SHEET

AUTHOR

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PUBLICATION DATE 1989

TITLE

Waves recorded at Channel Light Vessel 1979-1985.

REFERENCE

Institute of Oceanographic Sciences Deacon Laboratory, Report, No.263, 65pp.

ABSTRACT

Measurements of waves have been made routinely at Channel Light Vessel using a Shipborne Wave Recorder from 1979 to the present, with a few breaks in recording. This report analyses data taken up to 1985, and provides information detailing the location, instrumentation and data return. Obtained from the wave records are estimates of significant wave height, H_s, and zero-up-crossing period, T_z, the observed probability distributions of H_s and T_z are presented; the H_s distributions are fitted to appropriate extreme-value distributions which are then extrapolated to obtain estimates of the fifty-year return value of H_s. A new distribution is developed to attempt to account for the form of the observed cumulative distribution of H_s. Observed joint probability distributions of (H_s, T_z) and statistics of storm durations, with H_s above a specified threshold, are presented.

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KEYWORDS

CHANNEL/LV
ENGLISH CHANNEL(W)
EXTREME VALUES
NWEURCHANW
SHIPBORNE WAVE RECORDER
SIGNIFICANT WAVE HEIGHT
WAVE DATA

CONTRACT

PROJECT M1H-46-1

PRICE £18.00

Copies of this report are available from:
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CONTENTS

1. INTRODUCTION

Wave measurements have been recorded routinely at Channel Light Vessel from 1979 to the present, with occasional breaks in recording. This report describes the estimation of significant wave height, H_S, and zero-up-crossing period, T_Z, from chart records of sea surface elevation. Records taken up to 1985 are analysed; wave climate information, as derived from H_S and T_Z is presented.

2. LOCATION

The site at which the wave measurements were taken is shown in Figure 1. It is approximately 56 km WNW of Alderney, in a central position in the Western English Channel at 49°54'.3N 2°55'.3W, where the water depth is approximately 66m. The site is open to winds from WNW to SW, and from ENE to ESE. From other directions, the fetch is limited by the French and English mainlands, and the Channel Isles, between 60 and 120 km distant. The tidal currents in the area are strong, reaching a maximum of about 2.5 knots, with directions of approximately 070° and 250°. This may cause an apparent increase in the steepness of the waves; this effect would be most pronounced for short, low-period waves.

3. MEASUREMENT AND RECORDING SYSTEMS

Channel Light Vessel (LV) was fitted with a Shipborne Wave Recorder (SBWR) Mark II from 1979 to 1985; see Haine (1980) for a description of the device. The instrument provides information about the sea surface elevation which is recorded (usually) for a 12 minute period every three hours by pen on paper chart rolls. The method by which desired sea-state parameters (H_S and T_Z) are derived is described in Appendix I. After obtaining these parameters from chart records, two corrections need to be applied: one to compensate for the frequency response of the electronics of the SBWR, and one for the hydrodynamic attenuation of the pressure fluctuations with depth as measured by pressure sensing components of the SBWR. These corrections are described in some detail in Appendix I, but it is important to note here that the original scheme due to Tucker, and detailed, for example, in Crisp (1987) pp32-34, for correcting hydrodynamic attenuation of pressure fluctuations, is not used here. Pitt (1988a) develops a new and more accurate correction scheme, and it is this which has been applied to the data analysed here. This new scheme generally has the effect of reducing the measured value of H_S in a manner dependent on T_Z, ship length and pressure sensor depth. At Channel, the pressure sensor is deep mounted, so considerable alterations over the original correction scheme result, producing reductions of up to 20% in the corrected value of H_S. A comparison of the two correction schemes is presented in Appendix III. The pressure sensor depth is 2.0m. The length of the Light Vessel is 35m.

4. MAINTENANCE AND CALIBRATION

A 5254 (solid state type, or Mk.II) SBWR was deployed on Channel LV which began operation in September 1979, with a pressure sensor depth of 2.0m.

The instrument was calibrated in September 1981 during the LV refit. No change in sensitivity was found in the pressure sensors, but the accelerometers had changed by +4.4% (port) and +11.4% (starboard), so that wave heights were ultimately being over-read.

The instrument was again calibrated in November 1985 during the next LV refit. The pressure sensors were found to have changed sensitivity by -5.3% (port) and -6.1% (starboard, and the accelerometers by -15.3% (port) and -9.0% (starboard) so that wave heights were ultimately being under-read.

It has been assumed that the changes in sensitivity reported above occurred linearly with time. Corrections were effected on the following basis.

Using Crisp (1987), which shows the Channel LV SBWR frequency response, and Pitt (1988a) which shows how a certain pressure sensor calibration change affects SBWR response it was estimated that a change in pressure sensor sensitivity of the order of 5% would affect the subsequent estimate of H_S by the order of 1%, which was believed negligible, and so the pressure sensor calibration data have been omitted from this correction procedure.

That the accelerometers, when calibrated, had arrived at differing sensitivities allowed that the effect of the rolling of the LV was not averaged out. Using

Crisp (op.cit.), which shows the Channel LV roll response, it could be inferred that this would affect negligibly the final estimate of H_s.

Therefore the data were corrected assuming calibration changes given in magnitude by the mean accelerometer change for each period, and of opposite sense.

The main source of unquantifiable error lies in the assumption that the sensitivity changes were linear in time.

IOSDL staff were responsible for calibrations.

5. WAVE DATA COVERAGE

Table 1 gives the total return of valid records per month. The total data return and the data return per season are given below, where the seasons are defined as follows:

Spring:	March to May
Summer:	June to August
Autumn:	September to November
Winter:	December to February

Total number of valid records:		15528
Total from	Spring	3967
	Summer	4183
	Autumn	3049
	Winter	4029

Table 2 gives the total return of calm records per month. A record is defined as 'calm' if, on a chart record of sea surface elevation, the greatest crest height plus greatest trough depth does not exceed 0.5m. Where H_s data are grouped in 0.5m bins, H_s (calm) is set to $0 \leq H_s$ (calm) <0.5m; for individual record calculations (e.g. monthly mean), H_s(calm) is set to 0.25m.

6. DERIVATION OF SEA STATE PARAMETERS

When sample frequency spectra are available, significant wave height H_s is defined as $4\sqrt{m_0}$, and zero-up-cross period T_z as $\sqrt{(m_0/m_2)}$, where m_0 is the zeroth moment of the spectrum (equal to the sea surface variance), and m_2 the second moment. However, chart records do not readily provide spectral information, so a different method for extracting these parameters is used, the theory of which is available in works by Cartwright (1958) and Longuet-Higgins (1952); the practical application is described in papers by Tucker (1961) and Draper (1963). Critical reviews of this work are available in Tann (1976) and Crisp (1987); as mentioned previously, a brief summary is given in Appendix I.

Significant steepness, S_s, is defined by

$$S_s = \frac{2\pi H_s}{g T_z^2}$$

The fifty-year return value of H_s, $H_s(50)$, is defined as the value of H_s which is exceeded on average once in fifty years.

7. SUMMARY ANALYSIS OF WAVE CLIMATE DATA

7.1 Statistics of significant wave height

The maximum value of H_s recorded at Channel LV occurred on 15th December 1979 at 0900 hours with H_s = 10.90m and associated T_z = 11.80s. It is interesting that this is probably in excess of the fifty-year return value of H_s (for further discussion of which, see below). The second and third highest recorded values of H_s occurred within the same storm on the same day: 1200 hours, H_s = 9.89m with T_z = 11.61s, and 0300 hours, H_s = 9.59m with T_z = 10.99s. The fourth highest value, which is the highest recorded outside this storm, occurred on the 23rd November 1984 at 1800 hours, with H_s = 8.27m and associated T_z = 8.78s. The H_s values for the December 1979 storm are plotted in Figure 2, together with wind speed and direction measured on Channel LV, and also, for comparison, simultaneous H_s measurements from Seven Stones LV. The storm resulted from a depression which had formed west of Ireland on the 14th and moved east across

Ireland and North England on the 15th. The associated winds in the English Channel were westerly, reaching a peak of 55-60 knots (Force 11). The storm peaked at Seven Stones LV six hours earlier than at Channel LV.

Estimates of the probability distributions of H_S are shown in Figure 3 which present histograms giving the percentage occurrence over all data and over each season, with the H_S values grouped in 0.5m bins. These histograms are the marginal H_S distributions from the joint $H_S:T_Z$ histograms ('scatterplots') which were constructed allowing for the variation in the number of records per month. The probability values for each bin and each histogram are set out in Table 2.

Estimates of the cumulative H_S non-exceedance probability distributions, presented as ogives, are given in Figure 4. These were calculated in the same manner as the histograms above, but with H_S values grouped in 0.1m bins to smooth the curves.

For each month over all data, values were produced for H_S of the mean, maximum, median and 90th percentile; these values are presented in Tables 8-11 respectively. Figures marked with an asterisk indicate 10-20% missing data; figures in parentheses indicate >20% missing data; figures underlined indicate the maximum for the calendar month over all years.

Estimates of the fifty-year return value of H_S, $H_S(50)$, were obtained by fitting either a Fisher-Tippett Type I (FT1) or a Weibull distribution either to the observed distribution of H_S or to monthly maxima and extrapolating to the required probability. See Appendix III for details of fitting methods. A summary of values of $H_S(50)$ and fitted distribution parameters is given in Tables 4a and 4b. Figures 5, 6 and 7 show the cumulative probability distribution of all H_S data and (respectively) the fitted FT1, 3- and 2-parameter Weibull distributions.

The highest fifty-year return value of H_S is given by the fitting of the FT-1 distribution by maximum likelihood to monthly maxima: $H_S(50) = 12.84$m. That this estimate is dominated by the December 1979 maximum can be seen by the effect of removing that single value from the data: $H_S(50)$ falls to 11.86m. These estimates must be treated with caution, since only five or six values are available for each calendar month, and contrary to usual practise, months with less than 80% valid data were not excluded from the computation. Furthermore, both of these estimates are considerably higher than any of the estimates found by fitting the grouped distribution of all data, by method of moments, to the FT-1 and Weibull distributions, which give (3-parameter Weibull) 10.09m, (FT-1) 10.55m, and (2-parameter Weibull, all above 2.5m) 10.97m. Of the individual years fitted to FT-1 distribution, September 1979 to August 1980 (including the highest storm) gives the highest $H_s(50)$, 11.40m, but 1984 also gives a high value, 11.20m. The other available individual years give values from 9.10m to 10.83m. It is interesting that if one extrapolates by eye from the upper 1% of the whole data set, plotted on FT-1 paper, the resulting value of $H_s(50)$, 13.1m, is comparable with the seeming over-estimate obtained by the FT-1 fit by maximum likelihood to monthly maxima, 12.8m.

The grouped data were also plotted on Fisher-Tippett Type 2 and Log-Normal papers, but as no good fit was found, these are not shown.

It is notable that the data, when plotted on Weibull and FT-1 scales, diverge from straight lines in similar manners. In both cases (FT-1 and 3-parameter Weibull), reasonable fits of distribution to data are found below the 95% (corresponding to ~4.0m) level, but that the top 5% of the data have greater values of H_s than would be expected from extrapolation from the distribution of the lower data. It is possible that the measured wave climate is composed of samples of two distinct populations: a 'local' population, comprising the bulk of the data, and an 'oceanic' population, responsible for the measured extremes, which propagates up-Channel from the west and is generated by stormy events in the neighbouring area of the Atlantic Ocean/Western Approaches. It can be seen from Figure 2, for example, that the December 1979 storm resulted from strong westerly winds, in part of the narrow 'down-Channel' window where there is unlimited fetch.

A simple two-population model was developed to attempt to account for the manner in which the observed H_s distribution deviates from the 'normal' straight-line FT-1 type of distribution. Initially, the year of data September 1979 to August 1980 was grouped into 0.25m bins and the cumulative distribution formed. This year was chosen for its considerable sample of extreme wave heights. No allowance was made, as had been done previously, for the variation in the number of valid records per month throughout the year. It can be seen from Figure 8(a) that the distribution of the data can be described approximately as having a 'broken stick' form; i.e. there appear to be two separate straight line sections of the distribution (as plotted on FT-1 paper) with a 'break point' at about 95% probability, or H_s of 4m. this indicates that the data distribution could be represented by the sum of the two FT-1 distributions; one being a base (or 'mild') distribution which would represent the bulk of the data and would have FT-1 parameters similar to those found by the single FT-1 fit by method of moments (A=1.0m, B=0.8m): the other being a 'severe' or 'oceanic' distribution which would be present approximately 5% of the time (as estimated from the 'break point'), and would have an FT-1 location parameter similar to that from South Uist, for example, A=4.0m, and a slightly greater scale parameter than the base distribution, B=1.0m, to account for the decreasing slope of the data distribution as plotted on FT-1 scale. Accordingly, the model was fitted to the data in the following form.

$$\mathrm{Prob}(H_s \leq h) = (1-y)P_1 + yP_2$$

and

$$P_i = \exp(-\exp[-\{h-A_i\}/B_i]), \quad i=1,2$$

where y is the partition fraction between the two component FT-1 distributions and A_i, B_i their location and scale parameters. The model function was fitted to the data by least squares. As well as using the 1979-80 data, the cumulative H_s distributions were formed of the year August 1983 to July 1984, containing the highest event outside the 1979 storm, and of all data. A summary of the results is given below; the data and model functions are shown in Fig. 8.

Double FT-1 Parameters

Data Period	Partition Fraction (%)	A_1 (m)	B_1 (m)	A_2 (m)	B_2 (m)	$H_s(50)$ (m)
Sep. 79-Aug. 80	2.31	0.90	0.74	4.57	1.20	14.3
Aug. 83-Jul. 84	7.33	0.71	0.72	3.48	0.95	12.3
All	23.29	0.72	0.57	1.87	0.93	11.5

The 1983-84 data appear to fit well the estimated function values. This is also the case for the 1979-80 data, with the exception of the three uppermost points.

However, these points derive from the 1979 storm, and if this was a genuine extreme event (i.e. the one in 20 year or one in 60 year storm), they may be plotted at an unrepresentatively low probability. This latter may apply also to the whole data set. In estimating the function parameters for all data, it is not known whether there is a degree of 'trade-off' between the second ('severe') location parameter and the partition fraction: the best fit by least squares has produced in this third case large and (relatively) low values for these parameters (respectively).

It is difficult to recommend in this case a value for $H_s(50)$. Methods which estimate by extrapolation from the bulk of the data produce values of the order of 10 m to 11 m; methods which allow for the possibility that the extremes of the observed distribution may be distributed differently to the bulk of the data (2-parameter Weibull, Monthly Maxima, Double FT-1) produce estimates of between 11 m and 13 m. Unusually, a significant proportion of the tail of the observed H_s distribution appears differently distributed to the bulk of the data, so one is inclined to 'believe' the fitting methods which take account of this. The 2-parameter Weibull function, fitted to the top 15% of the data, estimates $H_s(50) = 10.97$ m; excluding the December 1979 value, which is unrepresentative in a 5-year sample, and fitting FT-1's to the remaining monthly maxima estimates $H_s(50) = 11.86$ m; the double FT-1 function appears to provide a good fit to the data, and estimates $H_s(50) = 11.5$ m. Therefore, the author recommends 11.5 m as the best estimate for $H_s(50)$.

Estimates were calculated of the probability distributions of the persistence of H_s above given threshold levels of H_s (also known as persistence of storms of H_s). See Figure 9, which shows plots of probability of exceedance of threshold versus minimum event duration for 2, 3, 4 and 5 m H_s thresholds; and Table 5, which gives the same statistics for thresholds from 2 m to 10 m in 0.5 m steps. Note that for the purpose of persistence only, gaps in the data of 3 (or less) H_s values were filled by linear interpolation. Longer gaps interfere with the calculation of individual storm durations; evidently, run lengths can only be truncated by such gaps. In order to clarify the meaning of the given figures, an outline of the method of calculation is given below.

Firstly, for each H_s threshold, the frequency distribution of storm duration was calculated (over all data). Outliers of duration greater than an arbitrary maximum (120 hours, or 5 days) were treated individually; these are given separately in Table 6. Table 5 gives data up to and including this maximum, but note that the outliers are included in these cumulative data. No allowance was made at this stage for interference with event duration consequent on truncation by gaps. Table 7 presents statistics of storm durations (mean number of events per year, mean event duration, etc) derived from these initial calculations. Next the 'reverse-cumulative' frequency distribution of minimum storm duration was calculated, producing for each duration the total of events of equal or greater duration. By this means, the lowest minimum duration (equivalent to one H_s record, or three hours) contains the total number of events above the given threshold, i.e. all events above the threshold were of one or more H_s records. In this form, the presentation is strictly correct, allowing for gaps. Finally, from this frequency distribution was calculated the equivalent probability distribution, by dividing each frequency by the total number of events measured above the relevant threshold. Example calculations, using these data (as in Tables 5 and 7) are given below.

Having ensured that the presence of gaps in the data did not impinge directly on the statistics of persistence as presented, there were in fact only four gaps in the recorded data of four or more records over H_s = 2 m at either or both ends of the gap; the gap-end values of H_s are given in Table 6b, showing that the statistics of 2.0, 2.5, 3.0 and 3.5 m were affected (with 4, 3, 1 and 1 events respectively). Therefore, if required, the data may be 'differenced' back into non-cumulative form with no loss of accuracy for data of 4m and above, and little loss below; see (iv) below. For this reason, the statistics presented in Table 7 may be used with confidence: i.e, mean number of events per year, mean event duration, etc.

Examples:

(i) What is the probability that if H_s increases above 3 m, it will remain above 3 m for nine hours or more? Table 5, row 3, col. 3, probability = 0.473, or ~47%.

(ii) What is the expected number of events per year with $H_s \geq 3$ m and duration ≥9 hours? Table 7, row 3, col. 3, mean number of events per year of $H_S \geq 3$ m is 53.2; probability x number of events = 26.2 per year.

(iii) On average in any year, for how long will conditions be of $H_S \geq 2$ m? Table 7, row 1, col. 5, 21.0% of total time finds $H_S \geq 2$ m, or a little under 77 days per year.

(iv) If H_S increases above 4 m, what is the probability that it will remain above 4 m for 6 hours? Table 5, row 5, cols. 2 and 3, prob($H_S \geq 4$; duration $\geq$6) = 0.724, prob($H_S \geq 4$; duration $\geq$9) = 0.560; so prob ($H_S \geq 4$; duration=6) = 0.724-0.560 = 0.164.

7.2 Statistics of zero-up-crossing period

Estimates of the probability distributions of T_Z are included in Figure 3; these histograms are computed in the same manner as the accompanying H_S histograms. The probability values for each bin and each histogram are set out in Table 4.

The maximum recorded value of T_Z occurred on 22 March 1984 at 1500 hours with T_Z = 15.82s and associated H_S = 0.93 m.

7.3 Statistics of the joint distribution of H_S and T_Z

Figure 10 shows the annual and seasonal joint probability distributions (or scatterplots) of H_S and T_Z with probabilities plotted in parts per thousand to the nearest integer. Included in these figures are lines of significant steepness of $^1/_7$, $^1/_{10}$, $^1/_{15}$ and $^1/_{20}$. When computing the scatterplots, allowance was made for the variation in the number of valid records per month throughout the year by computing a scatterplot for each calendar month, then combining the resulting monthly scatterplots (suitably weighted for different number of days per month) into plots representing the whole year and the seasons.

8. ACKNOWLEDGEMENTS

Thanks are due to Trinity House and the Masters of Channel LV for the installation and conscientious maintainance of the SBWR. Thanks are also due to numerous colleagues within IOSDL and others who were concerned over the years with the collection and processing of the data analysed in this report. The collection of the data and the preparation of this report were funded by the Ministry of Agriculture, Fisheries and Food.

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TABLE 1

Channel LV SBWR

Monthly Data Returns

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1979	-	-	-	-	-	-	-	-	232	221	240	241
1980	246	229	248	239	243	238	208	242	238	89	32	247
1981	247	224	248	234	245	238	248	244	185	138	239	247
1982	246	95	-	76	248	240	244	225	-	-	-	127
1983	240	222	246	233	248	239	244	244	237	247	239	243
1984	248	229	247	240	248	238	248	247	240	233	239	245
1985	242	212	239	239	246	237	247	112	-	-	-	-

TABLE 2

Channel LV SBWR

Monthly Calm Returns

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1979	-	-	-	-	-	-	-	-	107	47	13	8
1980	23	7	38	124	59	11	37	48	2	12	0	1
1981	3	2	0	47	3	80	39	98	21	8	10	1
1982	0	0	-	25	16	3	96	40	-	-	-	0
1983	18	1	2	19	14	74	121	99	1	29	40	12
1984	0	23	77	83	89	91	134	92	16	14	21	7
1985	2	8	7	40	41	62	53	2	-	-	-	-

TABLE 3A

Channel LV

H_S Histogram values (% occurrence)

Data Period	Calms	0.5	1.0	1.5	2.0	2.5	Bin Upper Limit (m) 3.0	3.5	4.0	4.5	5.0	5.5
All	14.94	2.54	24.89	20.70	14.85	9.47	5.15	3.04	1.85	1.07	0.65	0.30
Spring	17.19	2.11	29.45	22.23	12.51	7.46	3.76	2.64	1.15	0.73	0.40	0.11
Summer	28.28	5.04	36.21	18.39	8.07	2.55	0.94	0.34	0.14	0.05		
Autumn	11.12	1.80	21.46	22.99	19.30	11.01	5.21	2.81	1.85	0.91	0.60	0.24
Winter	2.88	1.17	12.19	19.18	19.67	17.01	10.81	6.44	4.29	2.61	1.62	0.87

Data Period	6.0	6.5	7.0	7.5	8.0	8.5	Bin Upper Limit (m) 9.0	9.5	10.0	10.5	11.0	11.5
All	0.25	0.11	0.07	0.03	0.05	0.02	0.00	0.00	0.01	0.00	0.01	
Spring	0.05	0.08	0.08	0.03	0.03							
Autumn	0.36	0.12	0.07	0.03	0.10	0.03						
Winter	0.59	0.24	0.15	0.07	0.07	0.05	0.00	0.00	0.05	0.00	0.02	

TABLE 3B

Channel LV

T_z Histogram values (% occurrence)

Data Period	Bin Upper Limit (s) 4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
All	0.13	0.57	1.87	3.64	6.74	11.56	12.56	10.39	9.80	8.30	5.97	5.17	2.76
Spring	0.03	0.36	1.75	3.76	7.02	10.61	11.98	8.92	10.21	7.41	5.79	4.95	3.18
Summer	0.23	1.51	4.17	5.88	7.83	12.00	10.45	7.81	7.02	5.63	3.56	2.63	1.22
Autumn	0.00	0.03	0.60	2.30	6.54	12.54	14.76	12.88	10.07	8.59	6.40	5.90	2.66
Winter	0.28	0.37	0.95	2.58	5.54	11.07	13.08	12.03	11.93	11.64	8.17	7.26	4.01

Data Period	Bin Upper Limit (s) 10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
All	2.05	1.52	0.74	0.53	0.33	0.18	0.08	0.06	0.05	0.02	0.03	0.01
Spring	2.40	1.84	0.66	0.56	0.51	0.46	0.16	0.08	0.05	0.05	0.03	0.03
Summer	0.80	0.41	0.25	0.29	0.03							
Autumn	1.93	1.53	0.93	0.55	0.29	0.03	0.07	0.13	0.07	0.00	0.09	
Winter	3.11	2.33	1.11	0.73	0.47	0.24	0.10	0.02	0.07	0.02		

TABLE 4A

Channel LV

50-Year Return Values of H_S

Function Type	Data Fitted	$H_S(50)$ (m)	A(location) (m)	B(Scale) (m)	C(Shape)
Fisher-Tippett Type I	All	10.55	0.93	0.81	-
	Spring	8.30	0.83	0.71	-
	Summer	5.29	0.57	0.45	-
	Autumn	9.22	1.04	0.78	-
	Winter	11.00	1.53	0.90	-
	9:1979-8:1980	11.40	0.92	0.88	-
	1980	10.34	0.97	0.79	-
	1981	9.10	0.91	0.69	-
	1983	10.83	0.94	0.83	-
	1984	11.20	0.85	0.87	-
	Monthly maxima	12.84			
	Monthly maxima (less 12:79 maximum)	11.86			
Weibull 2-parameter	All above 2.5m	10.97	-	1.35	1.18
Weibull 3-parameter	All	10.09	0.15	1.35	1.24

TABLE 4B

Channel LV

50-Year Return Values of H_S

Fisher-Tippett Type I fitted to Monthly Maxima

Month	A (location) (m)	B (scale) (m)	$H_S(50)$ (m)
1	4.95	1.11	9.28
2	5.05	1.12	9.41
3	4.89	0.90	8.41
4	3.10	1.42	8.64
5	3.14	0.50	5.09
6	2.87	0.63	5.32
7	1.88	0.46	3.66
8	2.43	0.46	4.21
9	3.45	1.26	8.35
10	4.35	1.05	8.45
11	4.19	1.71	10.85
12	6.32	1.42	11.85
(12)	(5.86)	(0.71)	(8.64)

TABLE 5

CHANNEL LV

Persistence of 'Storms' of H_S

H_S threshold (m)	Least Duration (Hours) 3	6	9	12	15	18	21	24	27	30
2.0	1.0	7.86E-1	5.40E-1	4.04E-1	3.39E-1	3.13E-1	2.68E-1	2.34E-1	1.91E-1	1.78E-1
2.5	1.0	7.45E-1	5.43E-1	3.84E-1	2.90E-1	2.46E-1	2.14E-1	1.75E-1	1.38E-1	1.17E-1
3.0	1.0	7.14E-1	4.73E-1	3.57E-1	3.00E-1	2.74E-1	2.24E-1	1.81E-1	1.59E-1	1.52E-1
3.5	1.0	7.17E-1	5.08E-1	3.69E-1	2.73E-1	2.25E-1	1.98E-1	1.71E-1	1.34E-1	1.12E-1
4.0	1.0	7.24E-1	5.60E-1	3.62E-1	2.84E-1	2.41E-1	1.98E-1	1.38E-1	1.03E-1	5.17E-2
4.5	1.0	7.65E-1	4.81E-1	3.09E-1	2.35E-1	2.10E-1	1.36E-1	7.41E-2	2.47E-2	1.23E-2
5.0	1.0	7.07E-1	4.66E-1	2.42E-1	1.55E-1	8.62E-2	5.17E-2	1.72E-2		
5.5	1.0	6.59E-1	3.41E-1	1.71E-1	9.76E-2	7.32E-2	7.32E-2			
6.0	1.0	6.80E-1	3.60E-1	1.60E-1	8.00E-2	8.00E-2				
6.5	1.0	5.79E-1	1.58E-1	5.26E-2	5.26E-2	5.26E-2				
7.0	1.0	5.45E-1	9.09E-2	9.09E-2	9.09E-2					
7.5	1.0	4.29E-1	1.43E-1	1.43E-1	1.43E-1					
8.0	1.0	3.00E-1	3.33E-1	3.33E-1	3.33E-1					
8.5	1.0	1.0	0.5							
9.0	1.0	0.5	0.5							
9.5	1.0	0.5								
10.0	1.0	1.0								

TABLE 5 (Continued)

Persistence of 'Storms' of H_S

H_S threshold	Least Duration (Hours)									
(m)	33	36	39	42	45	48	51	54	57	60
2.0	1.62E-1	1.44E-1	1.18E-1	1.05E-1	9.33E-2	8.84E-2	7.20E-2	6.55E-2	6.22E-2	5.40E-2
2.5	1.15E-1	9.66E-2	7.59E-2	6.44E-2	5.75E-2	5.29E-2	5.06E-2	4.37E-2	3.68E-2	2.99E-2
3.0	1.34E-1	1.05E-1	6.86E-2	5.42E-2	3.97E-2	3.25E-2	2.89E-2	2.53E-2	2.53E-2	1.44E-2
3.5	8.56E-2	5.88E-2	4.81E-2	3.21E-2	2.67E-2	1.07E-2	5.35E-3	5.35E-3		
4.0	3.45E-1	8.62E-2	8.62E-2	8.62E-2	8.62E-2	8.62E-2				

H_S threshold	Least Duration (Hours)									
(m)	63	66	69	72	75	78	81	84	87	90
2.0	4.91E-2	4.58E-2	4.41E-2	3.93E-2	3.11E-2	3.11E-2	2.78E-2	2.46E-2	2.29E-2	2.13E-3
2.5	2.99E-2	2.07E-2	2.07E-2	1.84E-2	1.84E-2	1.61E-2	1.15E-2	9.20E-3	6.90E-3	6.90E-3
3.0	1.44E-2	1.08E-2	1.08E-2	1.08E-2	1.08E-2	7.22E-3	7.22E-3	7.22E-3	7.22E-3	7.22E-3

H_S threshold	Least Duration (Hours)									
(m)	93	96	99	102	105	108	111	114	117	120
2.0	1.96E-2	1.96E-2	1.96E-2	1.80E-2	1.80E-2	1.80E-2	1.64E-2	1.64E-2	1.31E-2	1.31E-2
2.5	6.90E-3	6.90E-3	6.90E-3	6.90E-3	4.60E-3	4.60E-3	4.60E-3	4.60E-3	4.60E-3	4.60E-3
3.0	7.22E-3	7.22E-3	3.61E-3	3.61E-3	3.61E-3	3.61E-3				

TABLE 6A

Channel LV

Individual H_s 'storm' Outliers

H_s threshold (m)	Duration (hours)
2.5	246.4
2.0	255.2
2.0	187.8
2.0	168.2
2.0	129.2
2.0	135.9
2.0	133.7
2.0	162.1
2.0	180.7

TABLE 6B

Channel LV

Events Truncated by Gaps in Data

H_s Threshold (m)	H_s at Gap Start (m)	H_s at Gap End (m)
2.0	2.2	0.0
2.0	3.9	0.0
2.5	3.9	0.0
3.0	3.9	0.0
3.5	3.9	0.0
2.0	2.8	1.9
2.5	2.8	1.9
2.0	2.8	2.7
2.5	2.8	2.7

TABLE 7

Channel LV

Statistics of H_S 'storm' durations

H_S threshold (m)	Total No. of events	Mean No. of events per year	Mean duration (hours)	% of time above threshold	Variance of duration	Standard deviation of mean duration
2.0	611	117.3	15.71	21.02	471.01	0.878
2.5	435	83.5	12.58	11.98	279.01	0.801
3.0	277	53.2	11.95	7.25	227.19	0.906
3.5	187	35.9	10.44	4.27	123.09	0.811
4.0	116	22.3	9.72	2.47	81.72	0.839
4.5	81	15.5	8.24	1.46	48.04	0.770
5.0	58	11.1	6.67	0.85	27.41	0.687
5.5	41	7.9	5.74	0.52	24.74	0.777
6.0	25	4.8	5.46	0.30	16.29	0.807
6.5	19	3.6	4.18	0.17	12.89	0.824
7.0	11	2.1	3.95	0.10	12.27	1.056
7.5	7	1.3	4.07	0.06	19.29	1.660
8.0	3	0.6	5.50	0.04	48.00	4.000
8.5	2	0.4	6.00	0.03	4.50	1.500
9.0	2	0.4	4.50	0.02	18.00	3.000
9.5	2	0.4	3.00	0.01	4.50	1.500
10.0	1	0.2	4.50	0.01	0.00	0.000

Note: Mean number of events per year calculated based on total number of valid records equivalent to 5.21 years of data.

TABLE 8

Channel LV

Monthly Mean H_s

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1979	-	-	-	-	-	-	-	-	0.83	1.40	1.92	2.77
1980	1.73	2.24	1.77	0.62	0.83	0.99	0.99	1.05	1.22	1.63	1.99	2.05
1981	1.50	1.37	2.27	1.12	1.21	0.83	0.76	0.53	1.15	1.43	1.23	2.13
1982	2.14	2.09	-	0.60	0.92	1.15	0.60	0.86	-	-	-	1.86
1983	2.29	2.02	1.37	1.21	1.20	0.80	0.47	0.74	1.57	1.64	1.39	2.31
1984	2.79	1.84	1.11	0.87	0.72	0.69	0.69	0.61	1.14	1.80	2.10	1.91
1985	1.66	2.04	1.58	1.78	1.01	0.86	0.94	1.87	-	-	-	-

TABLE 9

Channel LV

Monthly Maximum H_s

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1979	-	-	-	-	-	-	-	-	2.28	4.12	5.58	10.90
1980	7.52	6.74	7.75	3.06	2.63	3.71	2.81	3.11	3.95	4.99	2.78	5.61
1981	4.35	4.06	6.25	3.08	3.69	2.86	1.57	2.21	4.03	3.27	3.12	6.17
1982	4.09	4.13	-	1.56	3.09	2.91	1.49	2.40	-	-	-	5.40
1983	5.83	5.79	4.44	7.41	3.14	3.22	1.83	2.05	7.69	5.59	6.14	8.17
1984	7.45	7.29	4.49	3.64	3.31	2.16	2.50	2.52	3.28	6.71	8.27	5.39
1985	4.52	5.97	4.51	4.86	4.86	4.48	2.66	4.05	-	-	-	-

TABLE 10

Channel LV

Monthly Median H_s

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1979	-	-	-	-	-	-	-	-	0.82	1.39	1.88	2.48
1980	1.46	2.05	1.56	0.25	0.81	0.83	0.91	1.01	1.07	1.49	2.00	1.85
1981	1.35	1.29	2.21	1.06	1.02	0.73	0.78	0.45	1.00	1.50	1.04	1.95
1982	2.16	2.05	-	0.58	0.83	1.05	0.66	0.81	-	-	-	1.44
1983	2.15	2.03	1.22	1.05	1.03	0.68	0.39	0.85	1.25	1.58	0.98	2.04
1984	2.54	1.60	0.98	0.81	0.55	0.61	0.25	0.49	1.07	1.60	1.77	1.79
1985	1.61	1.71	1.41	1.65	0.98	0.68	0.80	1.82	-	-	-	-

TABLE 11

Channel LV

Monthly 90th Percentile H_S

Year	Month											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1979	-	-	-	-	-	-	-	-	1.73	2.41	3.00	4.67
1980	2.95	3.94	3.38	1.26	1.43	1.74	1.79	1.83	1.99	3.80	2.68	3.43
1981	2.71	2.26	3.76	2.14	2.12	1.61	1.13	0.97	2.18	2.24	2.21	3.73
1982	3.09	3.12	-	1.00	1.50	1.82	1.02	1.45	-	-	-	3.95
1983	3.90	2.95	2.22	2.14	2.18	1.59	0.90	1.27	2.60	2.83	3.61	4.11
1984	4.72	3.56	2.26	1.70	1.45	1.36	1.64	1.27	1.98	3.14	3.93	2.97
1985	2.75	4.06	2.69	3.57	1.72	1.68	1.82	2.88	-	-	-	-

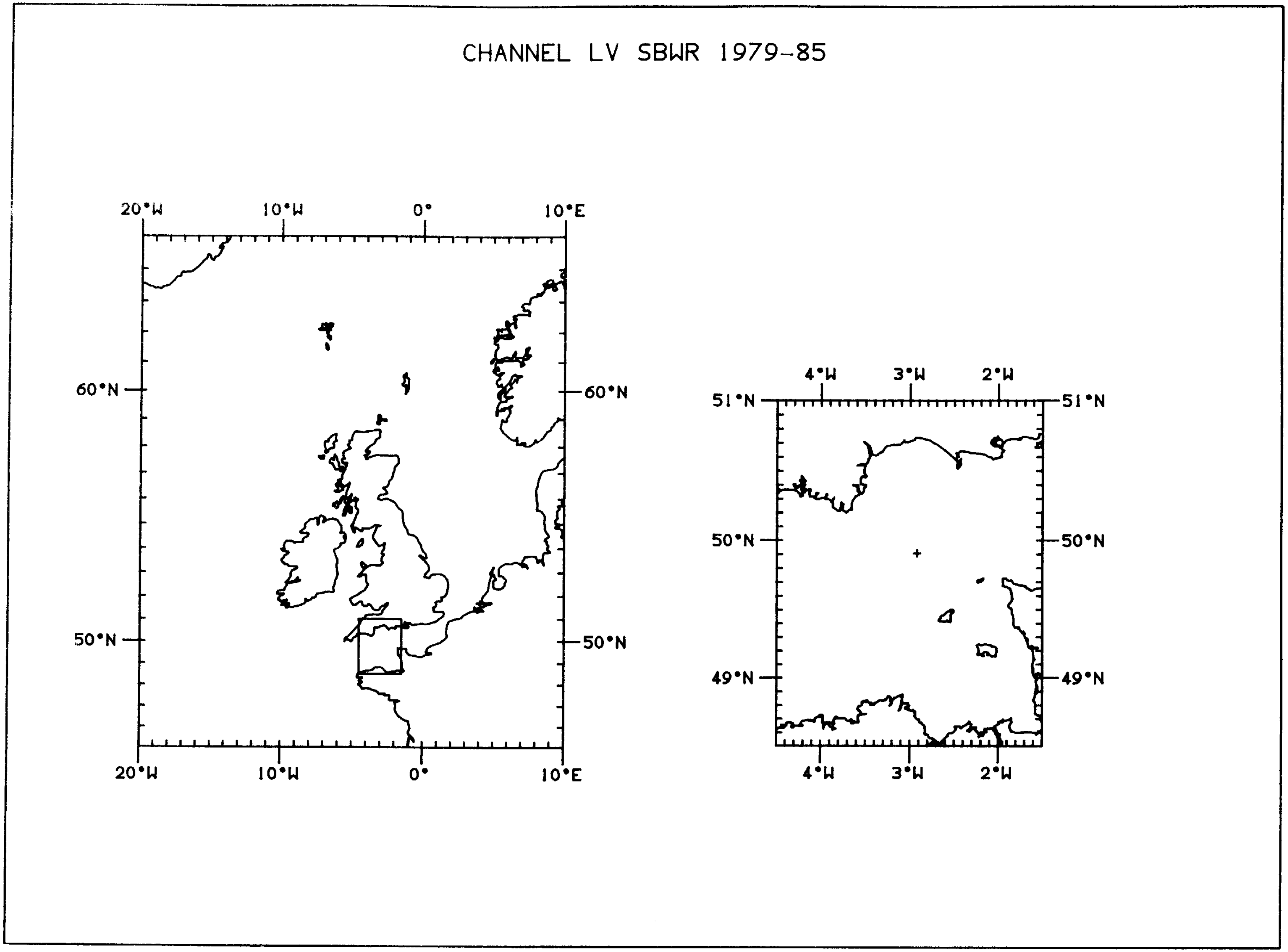

CHANNEL LV SBWR 1979-85
20°W
10°W
0°
10°E
60°N
50°N
4°W
3°W
2°W
51°N
50°N
49°N

Fig.1

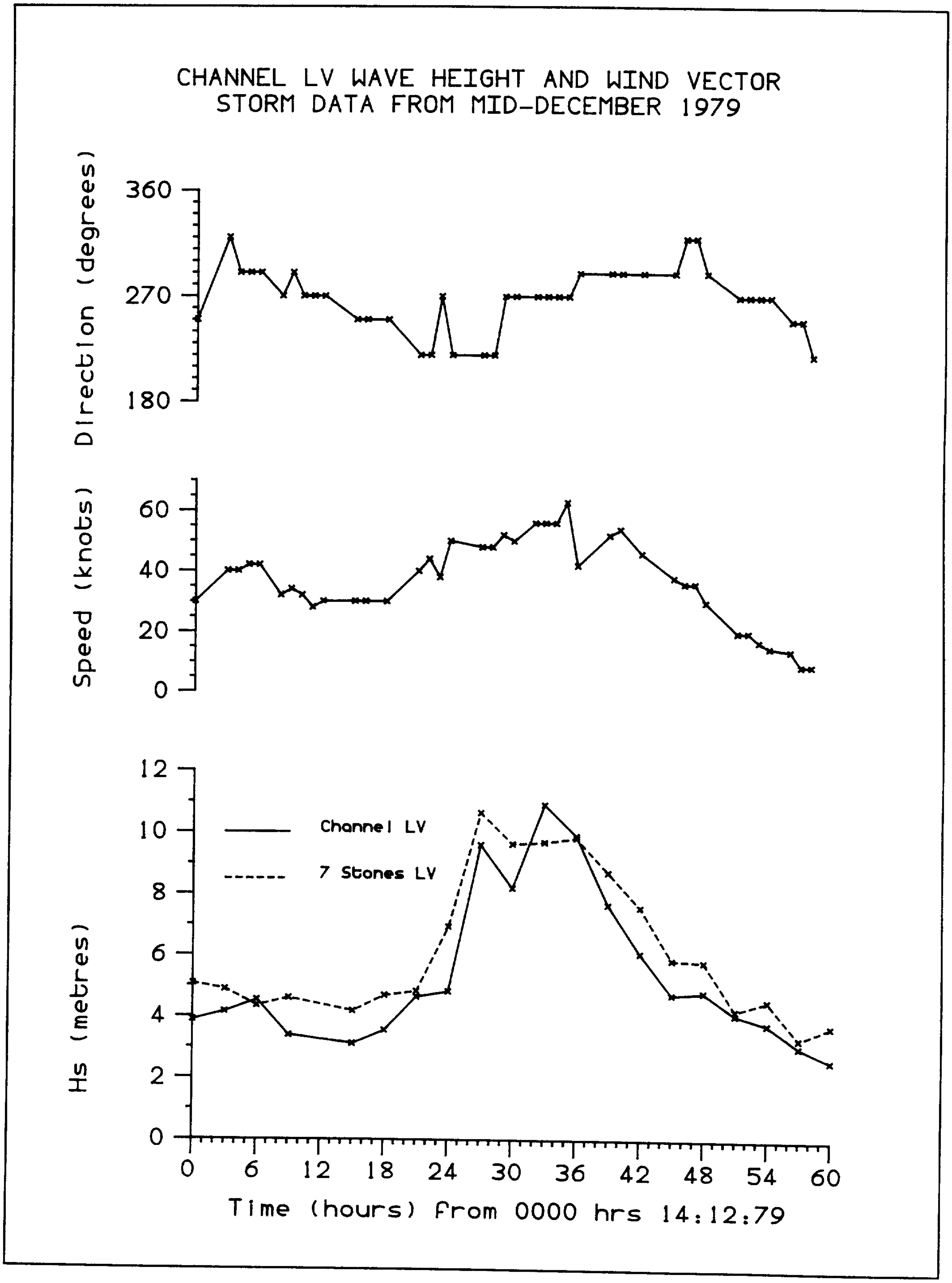

CHANNEL LV WAVE HEIGHT AND WIND VECTOR
STORM DATA FROM MID-DECEMBER 1979
Direction (degrees)
360
270
180
Speed (knots)
60
40
20
0
Hs (metres)
12
10
8
6
4
2
0
Channel LV
7 Stones LV
0
6
12
18
24
30
36
42
48
54
60
Time (hours) from 0000 hrs 14:12:79

Fig.2

CHANNEL LV SBWR 1979-85
Percentage Occurrence Histograms for Hs and Tz
ALL DATA

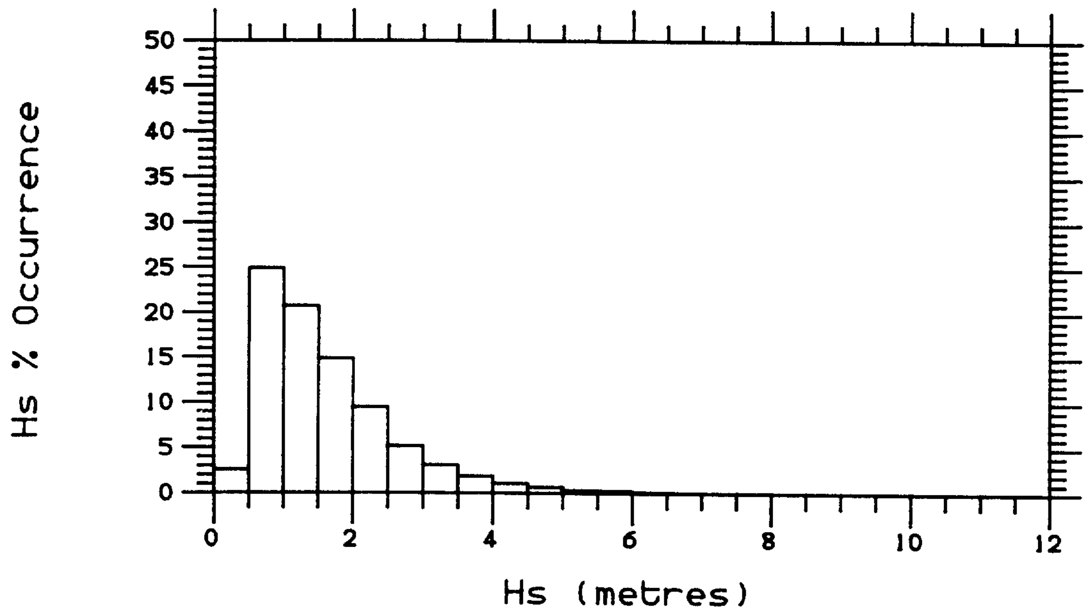


Fig.3(a)

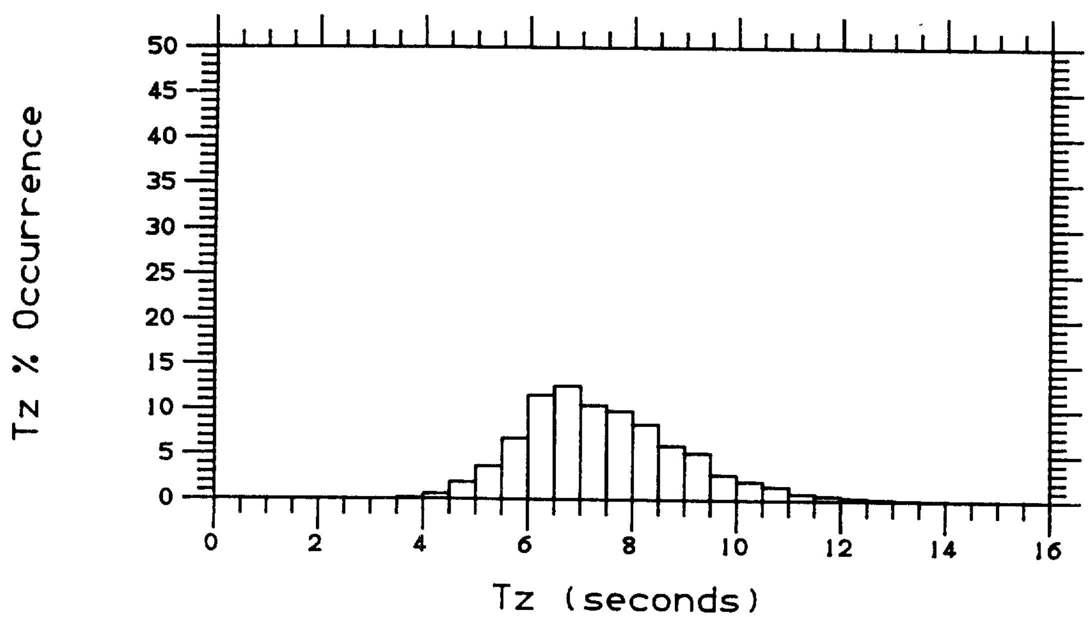


Fig.3(b)

CHANNEL LV SBWR 1979-85
Percentage Occurrence Histograms for Hs and Tz
SPRING

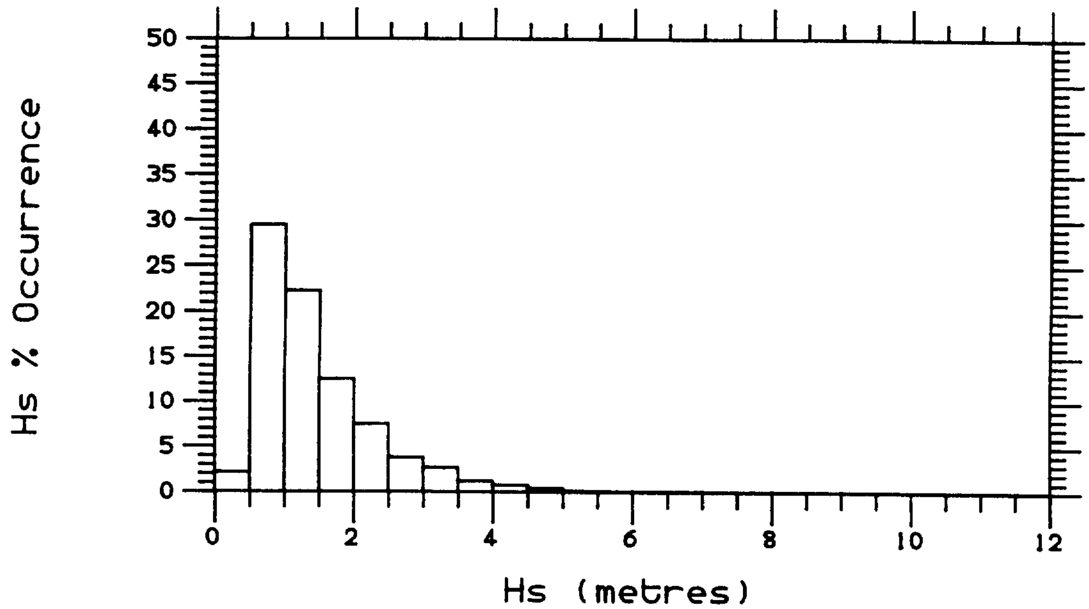


Fig.3(c)

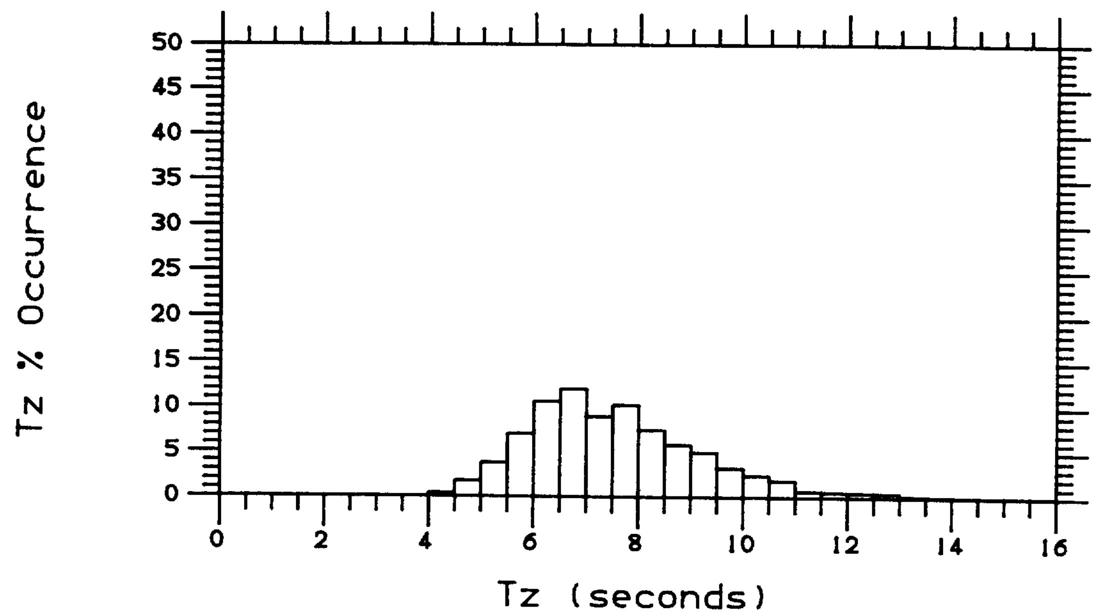


Fig.3(d)

CHANNEL LV SBWR 1979-85
Percentage Occurrence Histograms for Hs and Tz
SUMMER

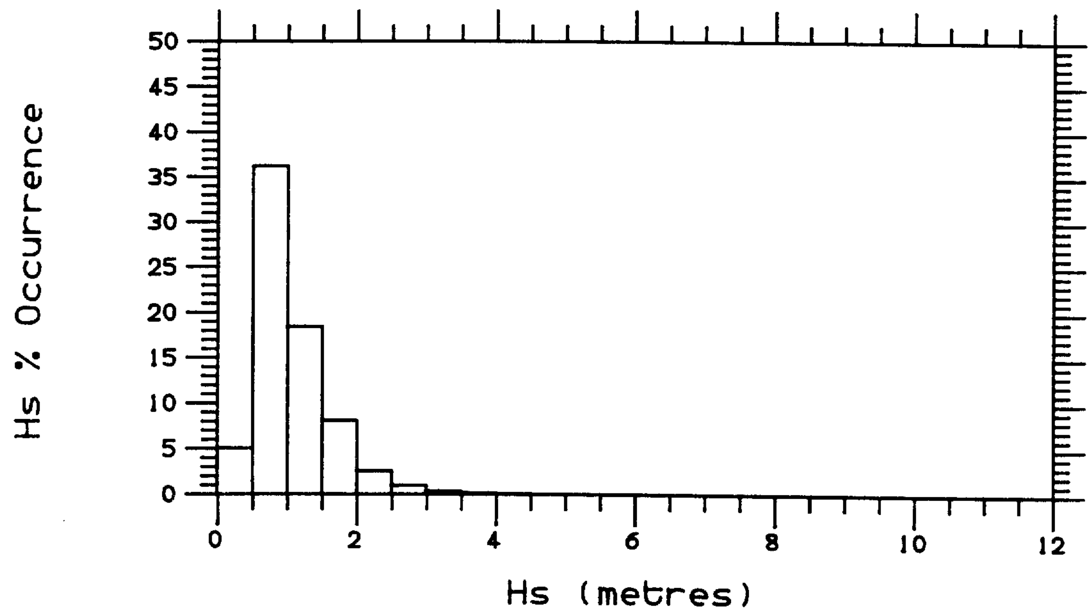


Fig.3(e)

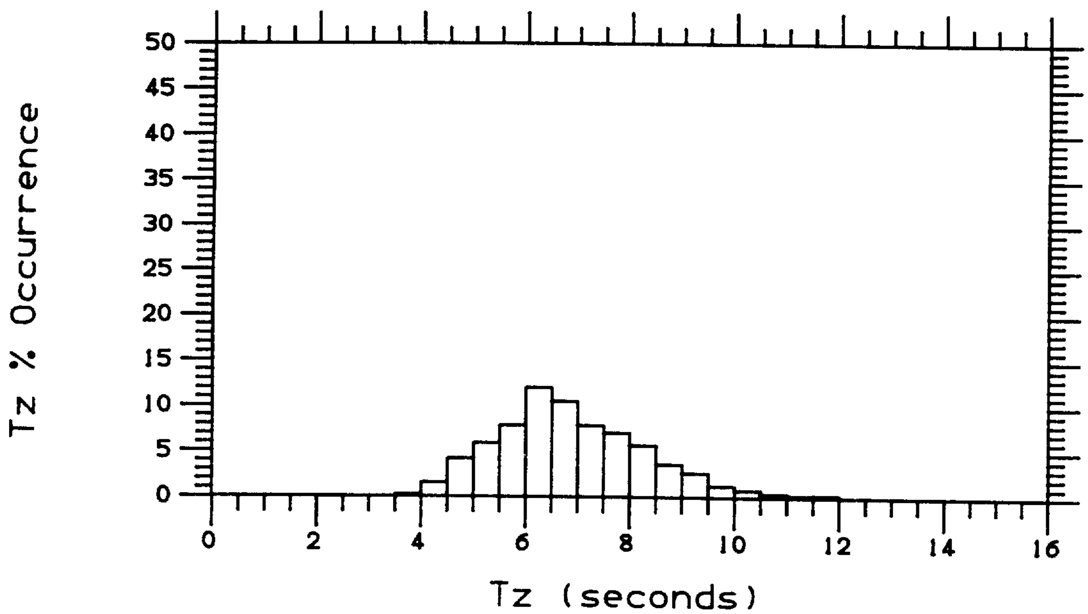


Fig.3(f)

CHANNEL LV SBWR 1979-85
Percentage Occurrence Histograms for Hs and Tz
AUTUMN

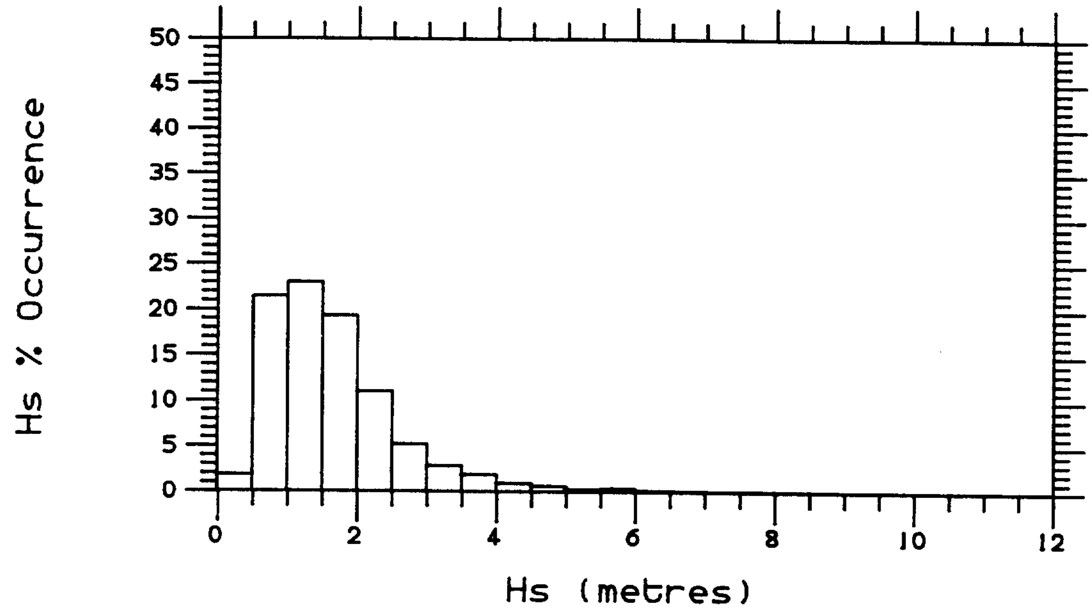


Fig.3(a)

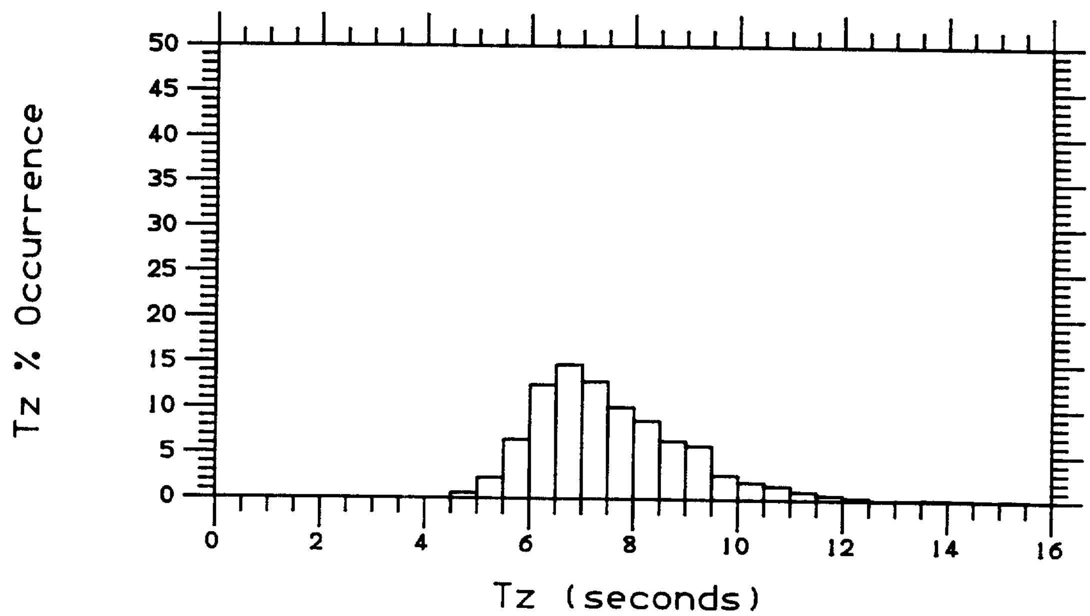


Fig.3(b)

CHANNEL LV SBWR 1979-85
Percentage Occurrence Histograms for Hs and Tz
WINTER

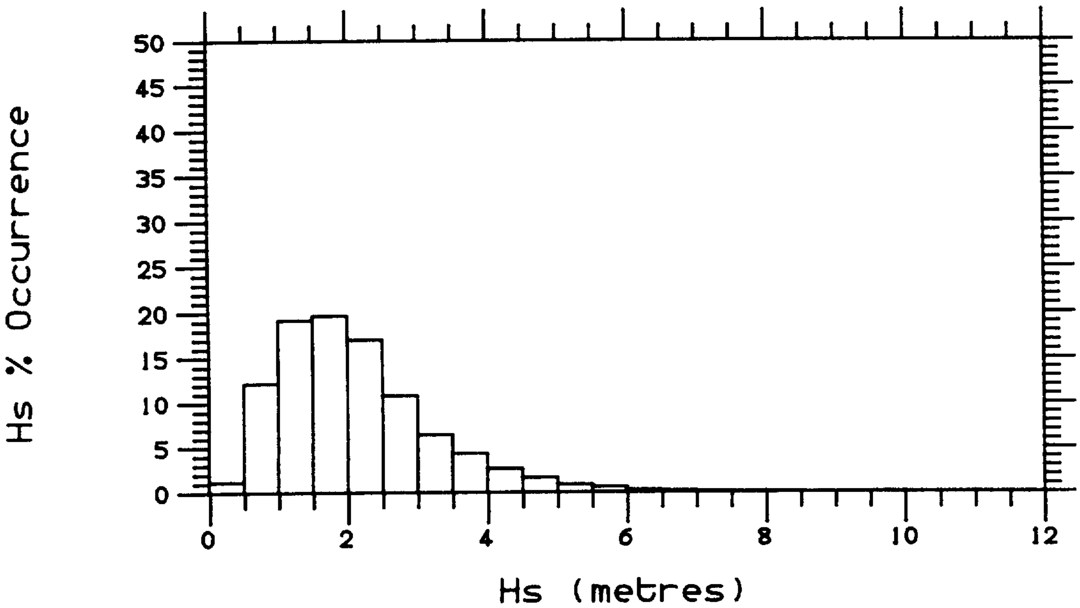


Fig.3(i)

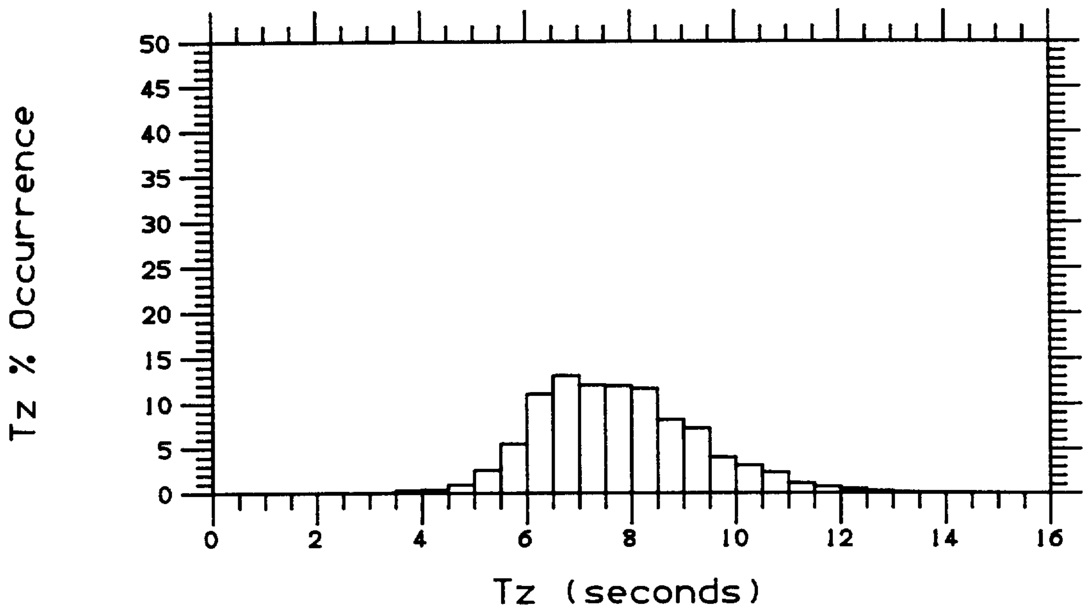


Fig.3(j)

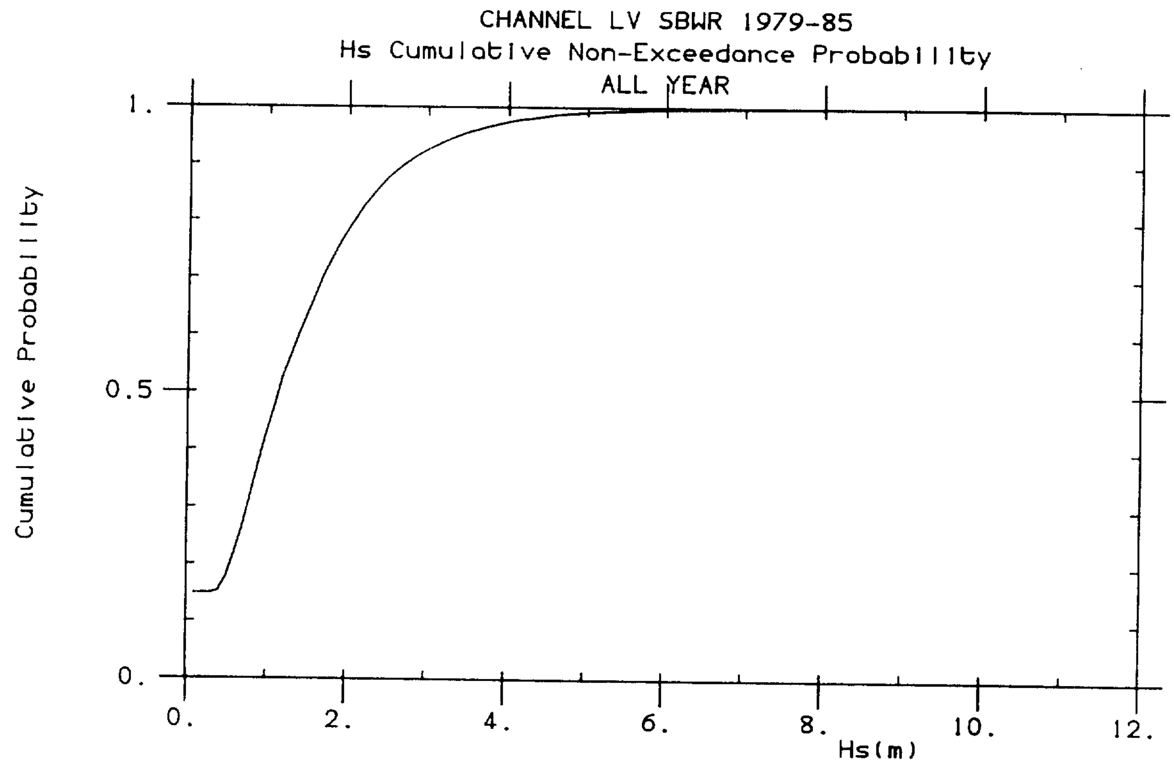

CHANNEL LV SBWR 1979-85
Hs Cumulative Non-Exceedance Probability
ALL YEAR
Cumulative Probability
1.
0.5
0.
0.
2.
4.
6.
8.
10.
12.
Hs(m)

Fig.4(a)

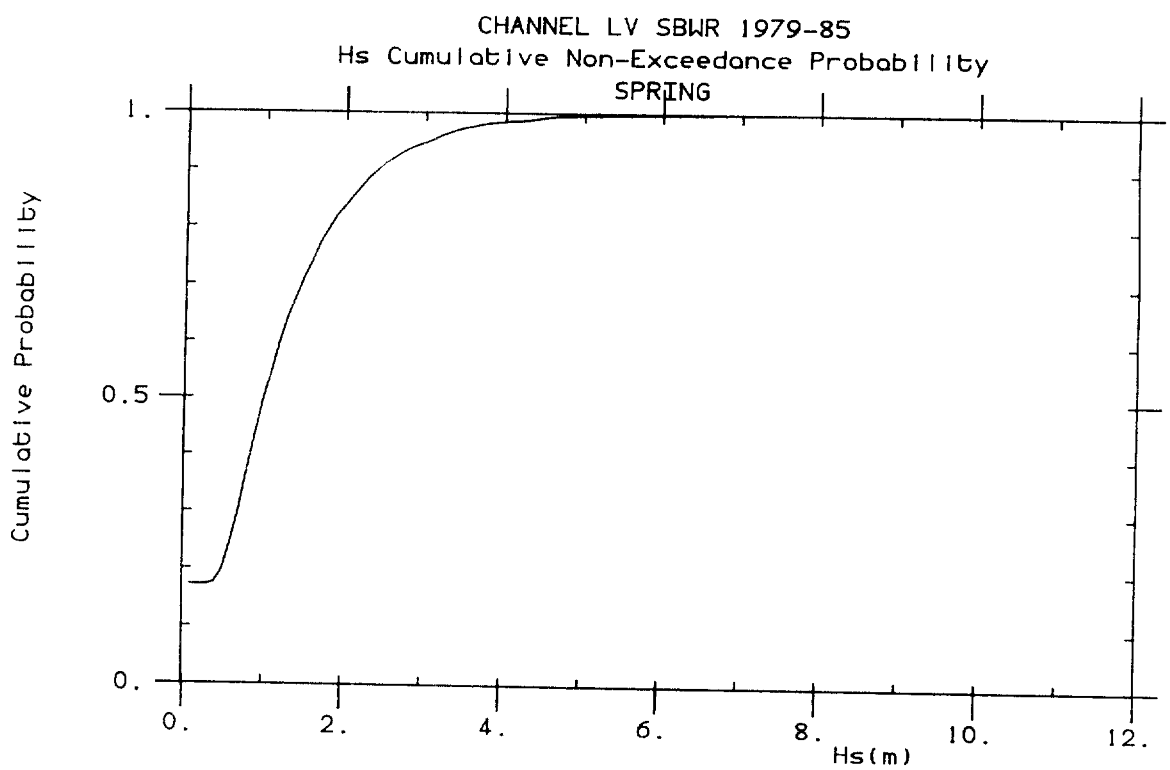

CHANNEL LV SBWR 1979-85
Hs Cumulative Non-Exceedance Probability
SPRING
Cumulative Probability
1.
0.5
0.
0.
2.
4.
6.
8.
10.
12.
Hs(m)

Fig.4(b)

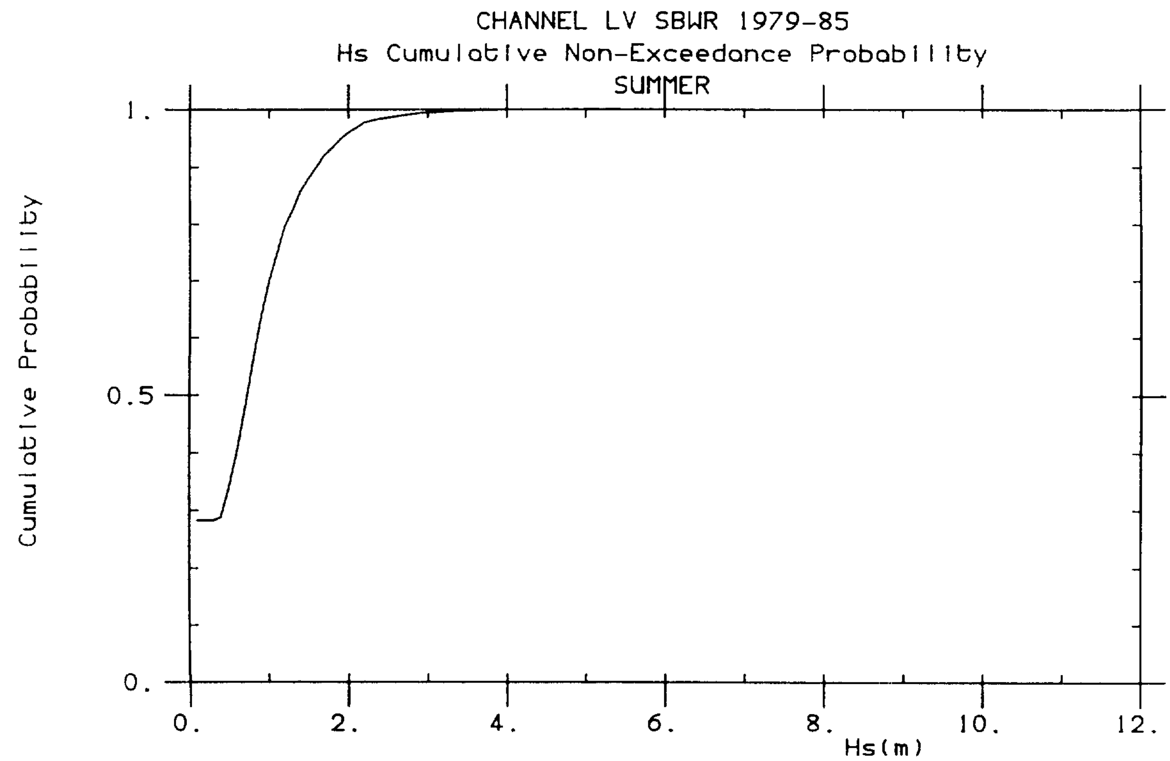

CHANNEL LV SBWR 1979-85
Hs Cumulative Non-Exceedance Probability
SUMMER
Cumulative Probability
1.
0.5
0.
0.
2.
4.
6.
8.
10.
12.
Hs(m)

Fig.4(c)

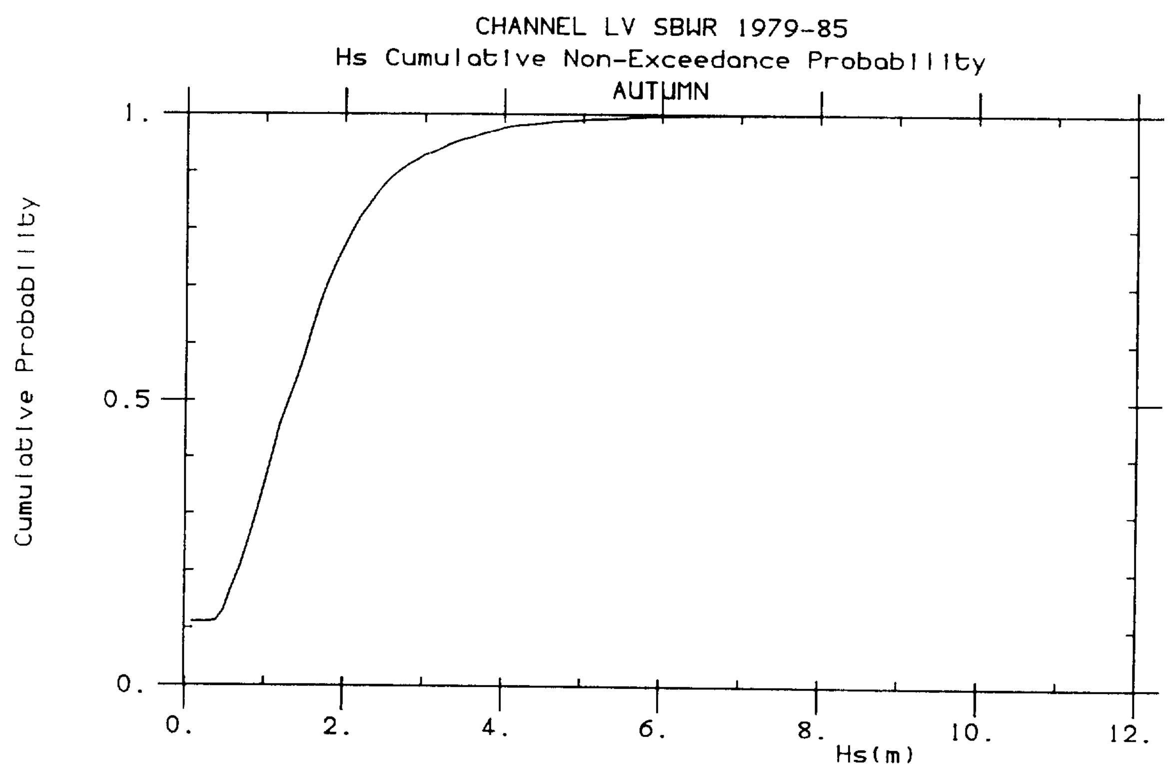

CHANNEL LV SBWR 1979-85
Hs Cumulative Non-Exceedance Probability
AUTUMN
Cumulative Probability
1.
0.5
0.
0.
2.
4.
6.
8.
10.
12.
Hs(m)

Fig.4(d)

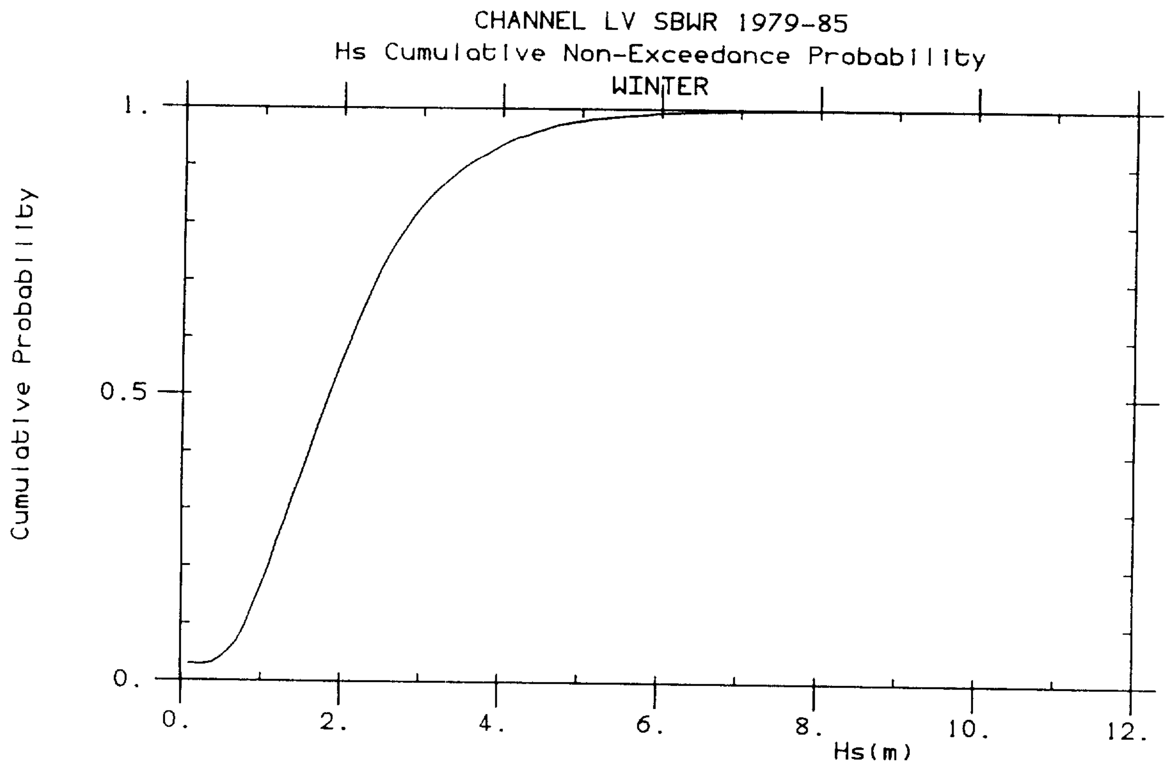

CHANNEL LV SBWR 1979-85
Hs Cumulative Non-Exceedance Probability
WINTER
Cumulative Probability
1.
0.5
0.
0.
2.
4.
6.
8.
10.
12.
Hs(m)

Fig.4(e)

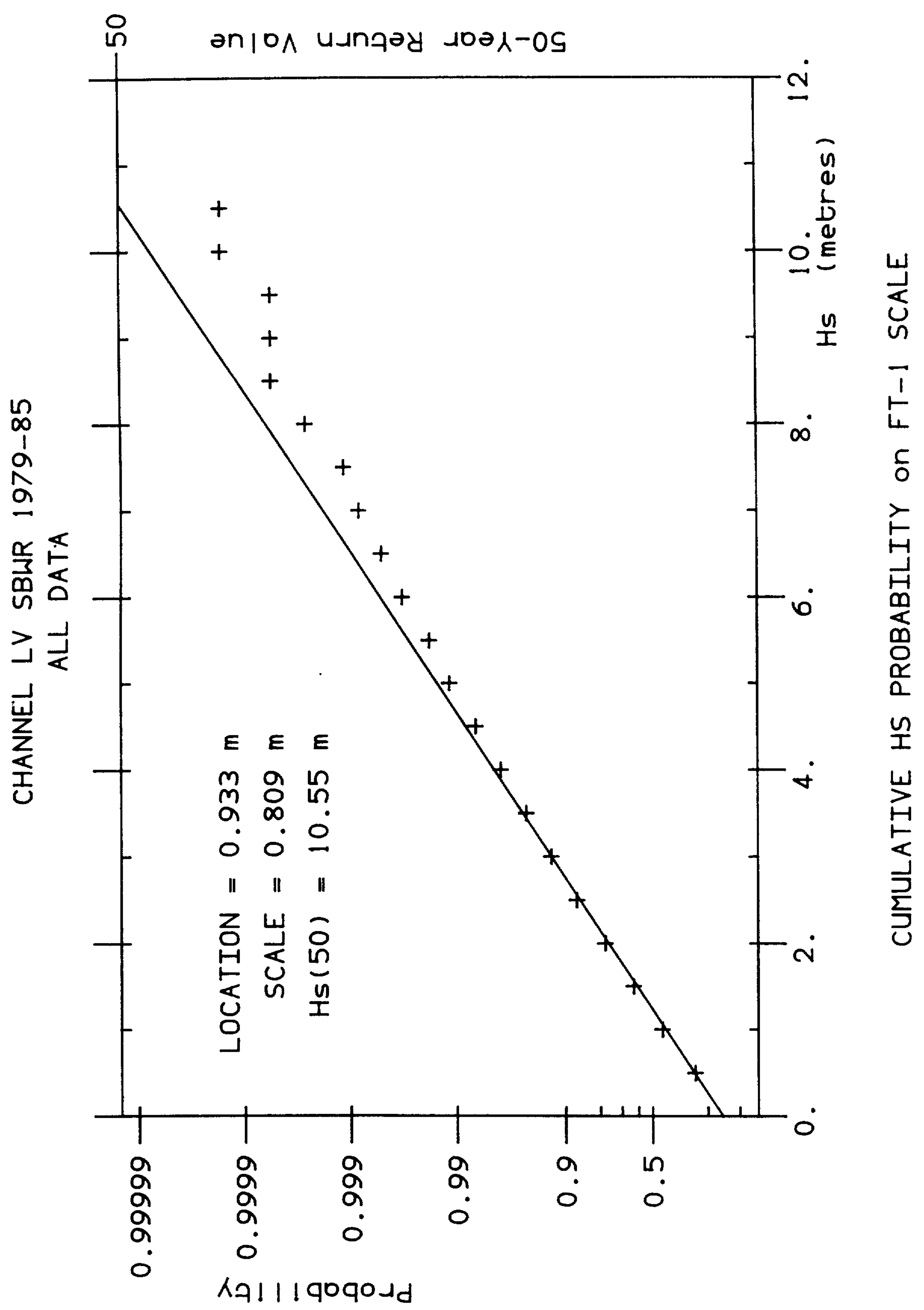
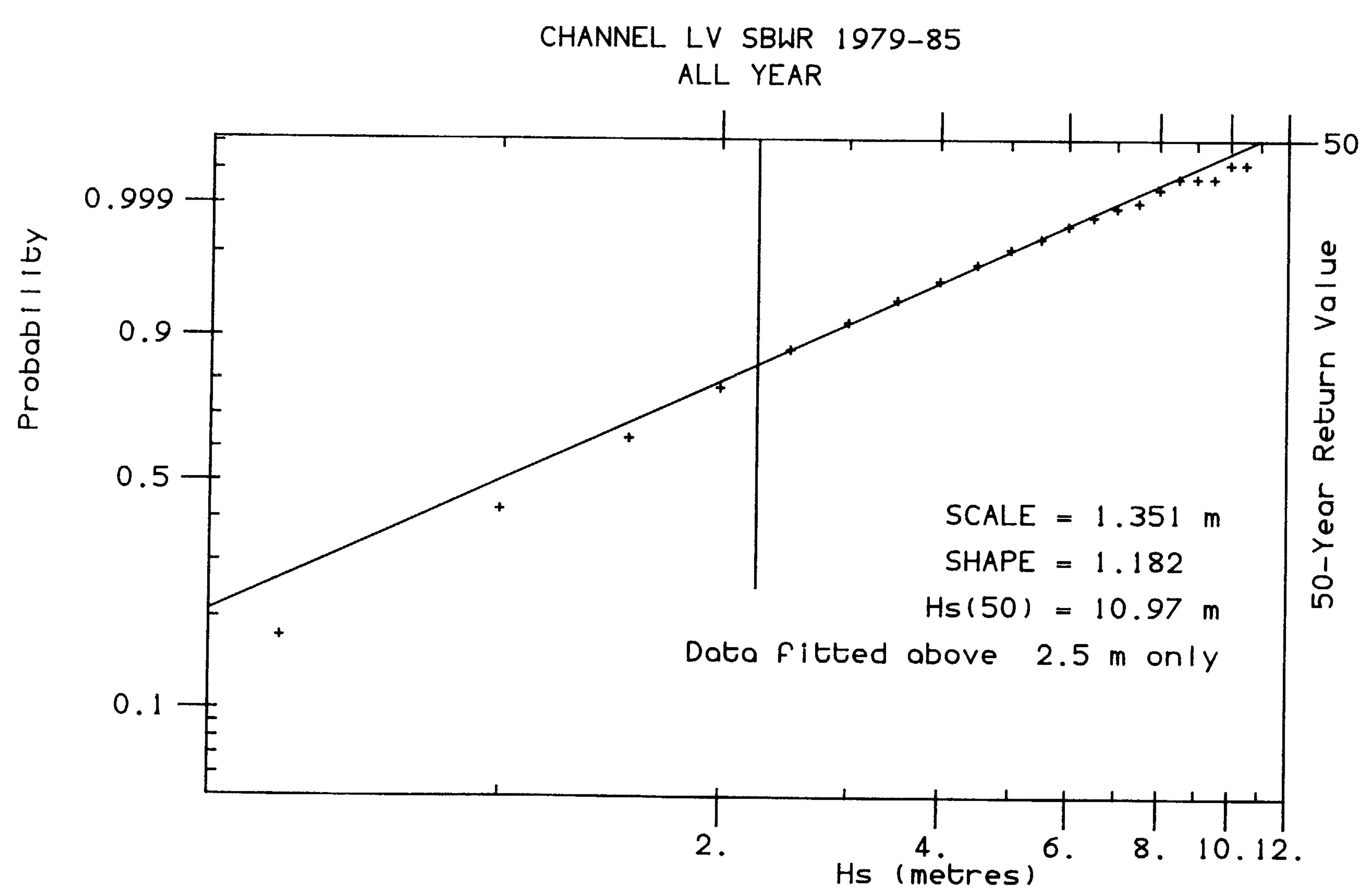

CHANNEL LV SBWR 1979-85
ALL DATA
LOCATION = 0.933 m
SCALE = 0.809 m
Hs(50) = 10.55 m
50-Year Return Value
50
Probability
0.99999
0.9999
0.999
0.99
0.9
0.5
0.
2.
4.
6.
8.
10.
12.
Hs (metres)
CUMULATIVE HS PROBABILITY on FT-1 SCALE

Fig.5



CUMULATIVE HS PROBABILITY on WEIBULL SCALE

Fig.6

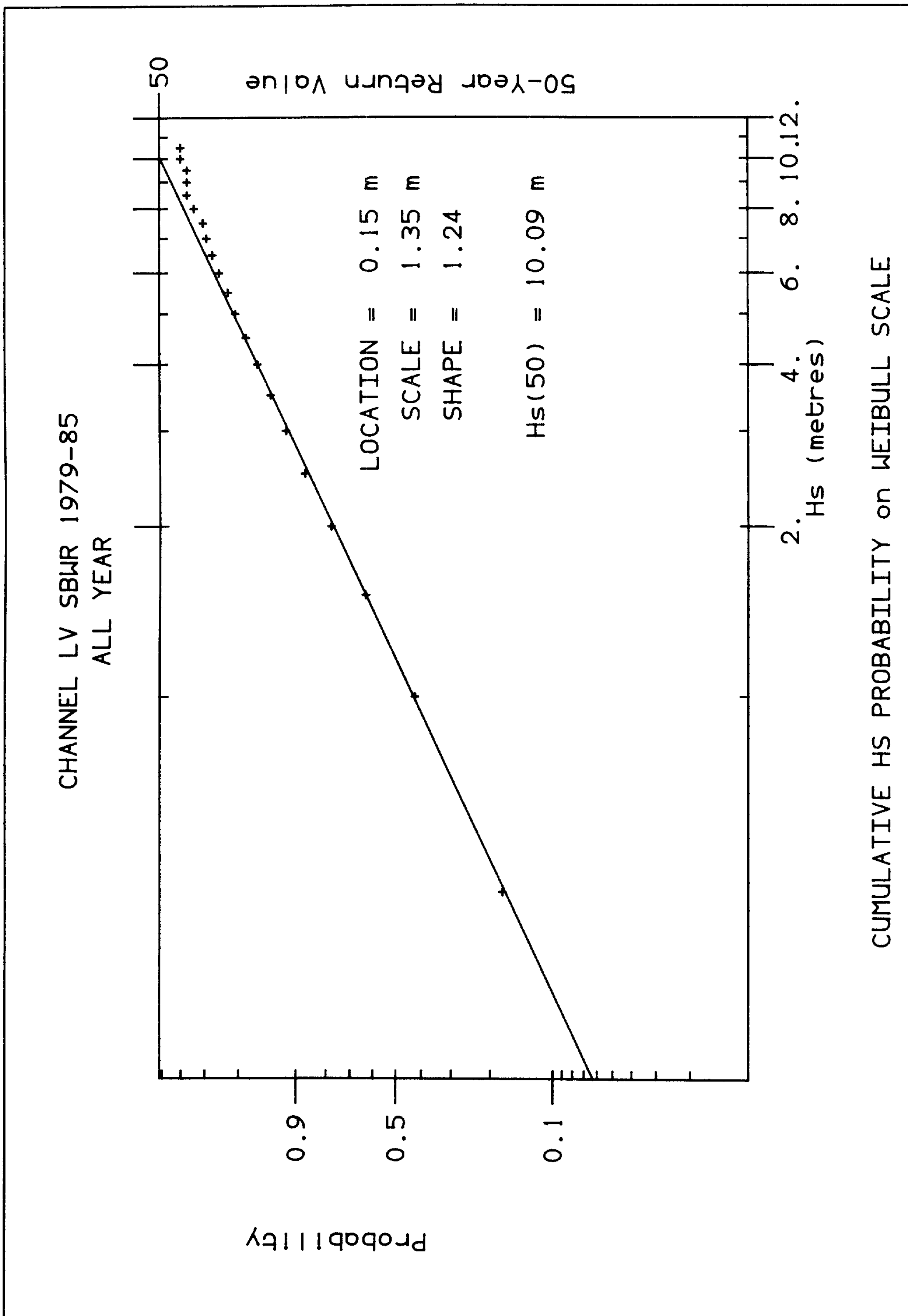

CHANNEL LV SBWR 1979-85
ALL YEAR
50-Year Return Value
50
LOCATION = 0.15 m
SCALE = 1.35 m
SHAPE = 1.24
Hs(50) = 10.09 m
Probability
0.9
0.5
0.1
2.
4.
6.
8.
10.
12.
Hs (metres)
CUMULATIVE HS PROBABILITY on WEIBULL SCALE

Fig.7

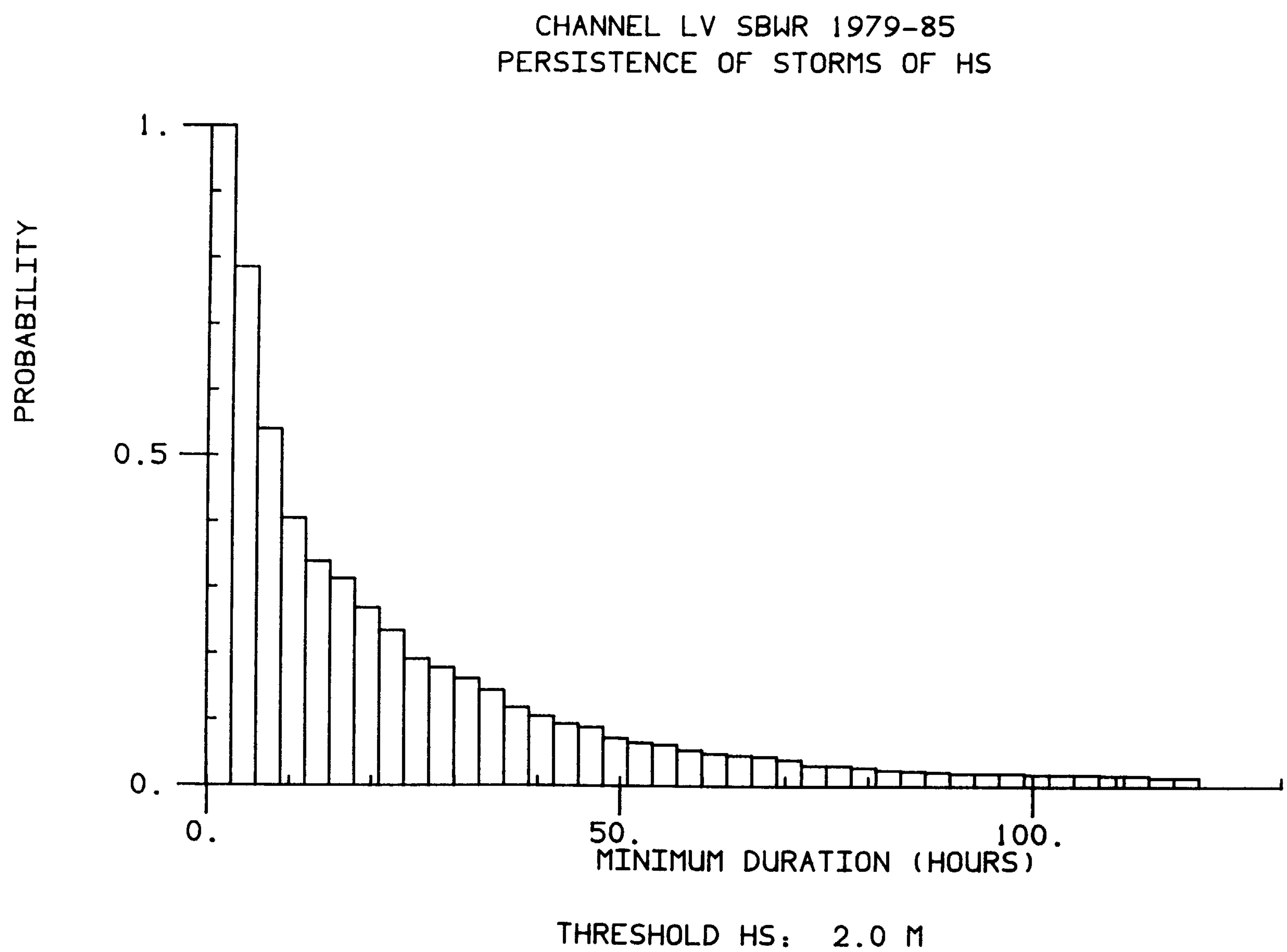

CHANNEL LV SBWR 1979-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 2.0 M

Fig.8(a)

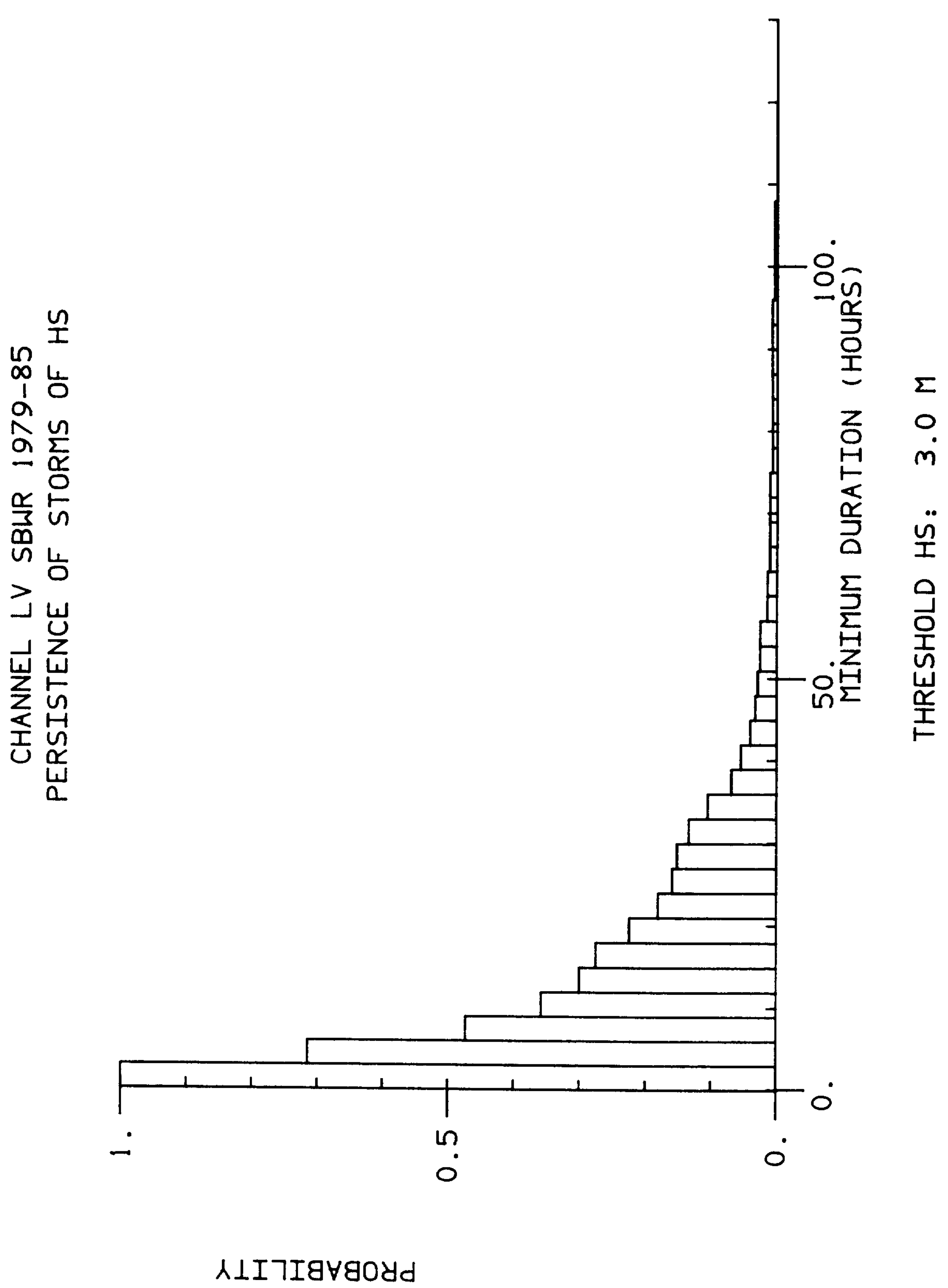

CHANNEL LV SBWR 1979-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 3.0 M

Fig.8(b)

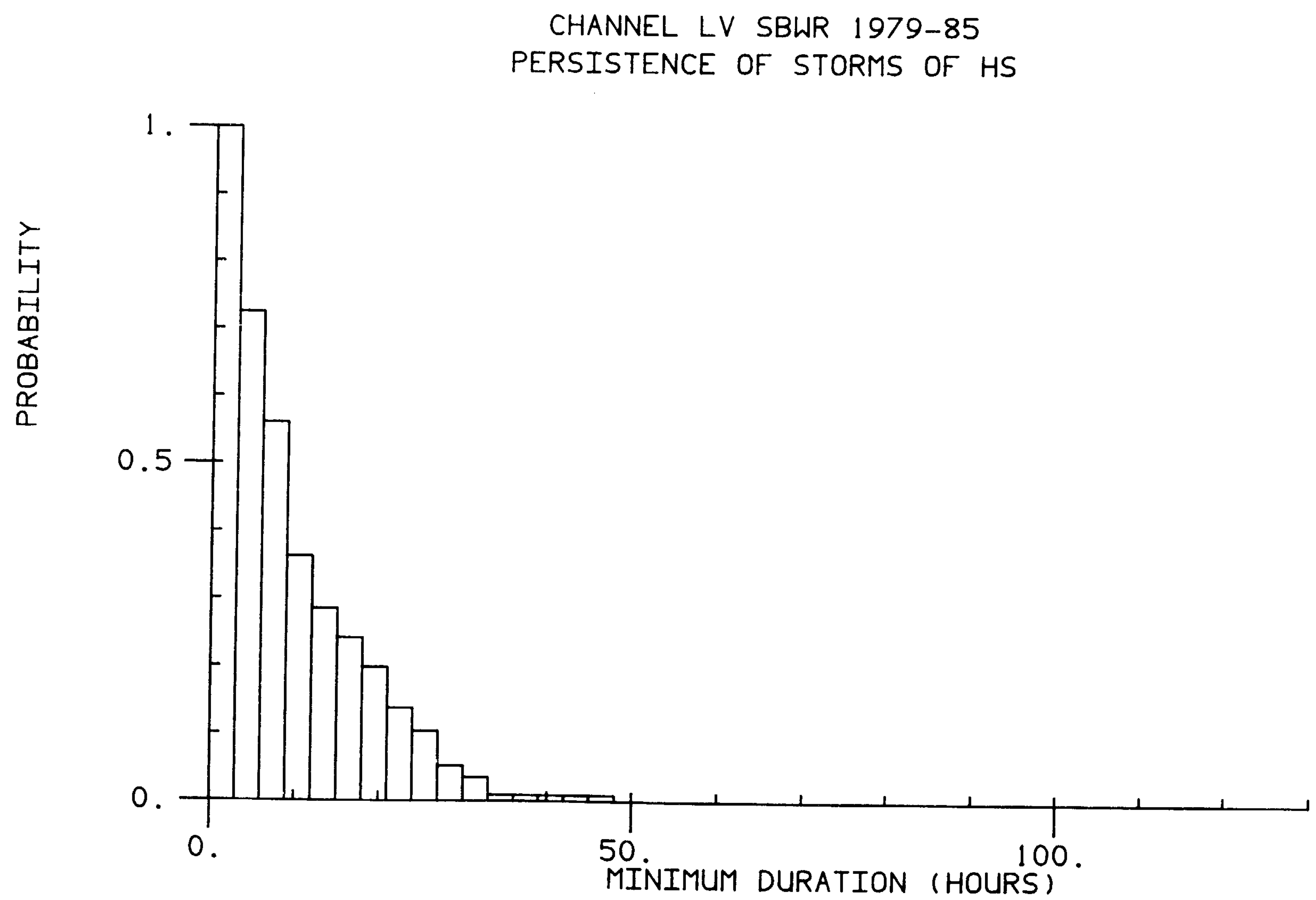

CHANNEL LV SBWR 1979-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 4.0 M

Fig.8(c)

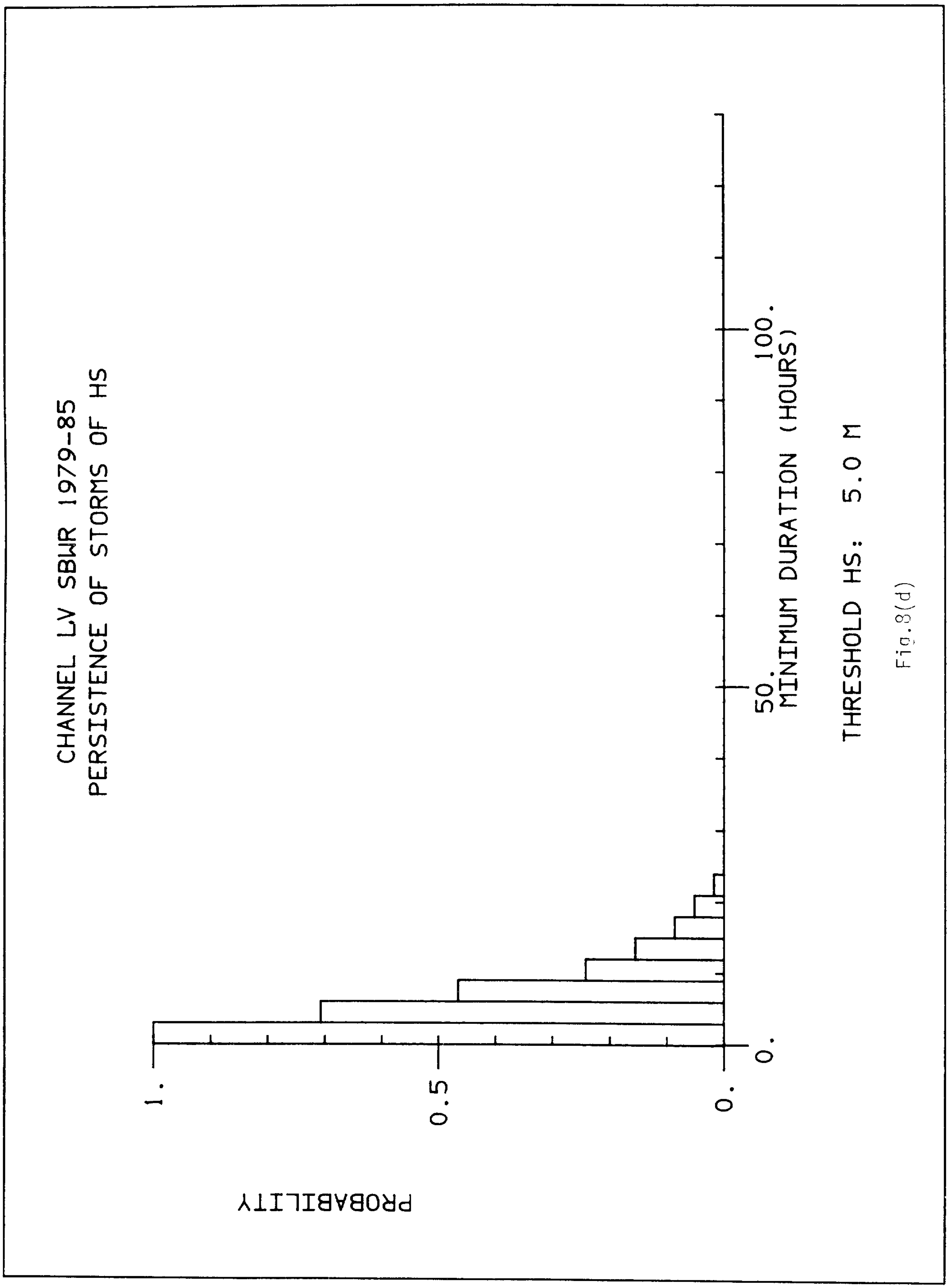

CHANNEL LV SBWR 1979-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 5.0 M

Fig.8(d)

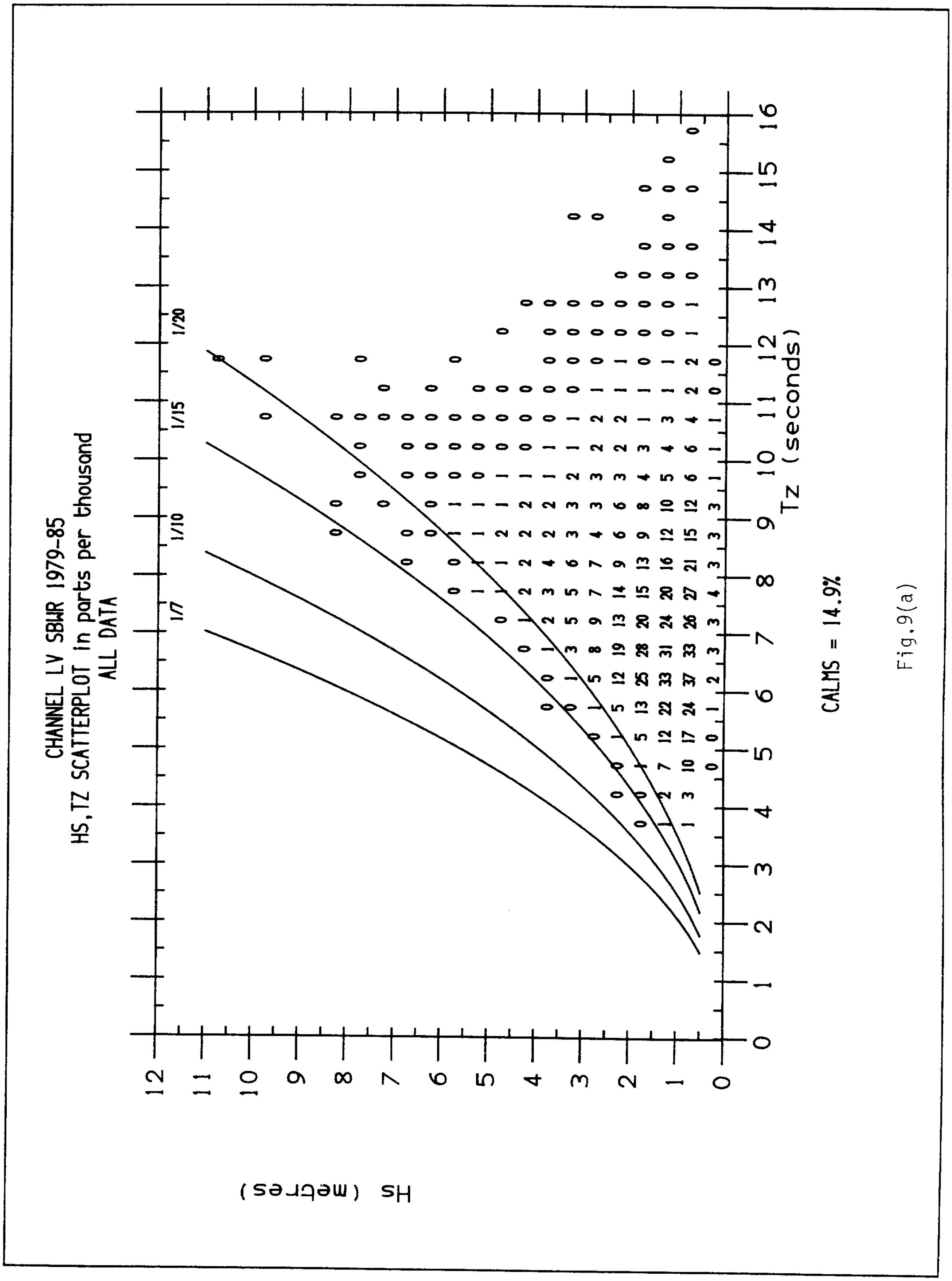

CHANNEL LV SBWR 1979-85
HS,TZ SCATTERPLOT in parts per thousand
ALL DATA
1/7
1/10
1/15
1/20
Hs (metres)
Tz (seconds)
CALMS = 14.9%

Fig.9(a)

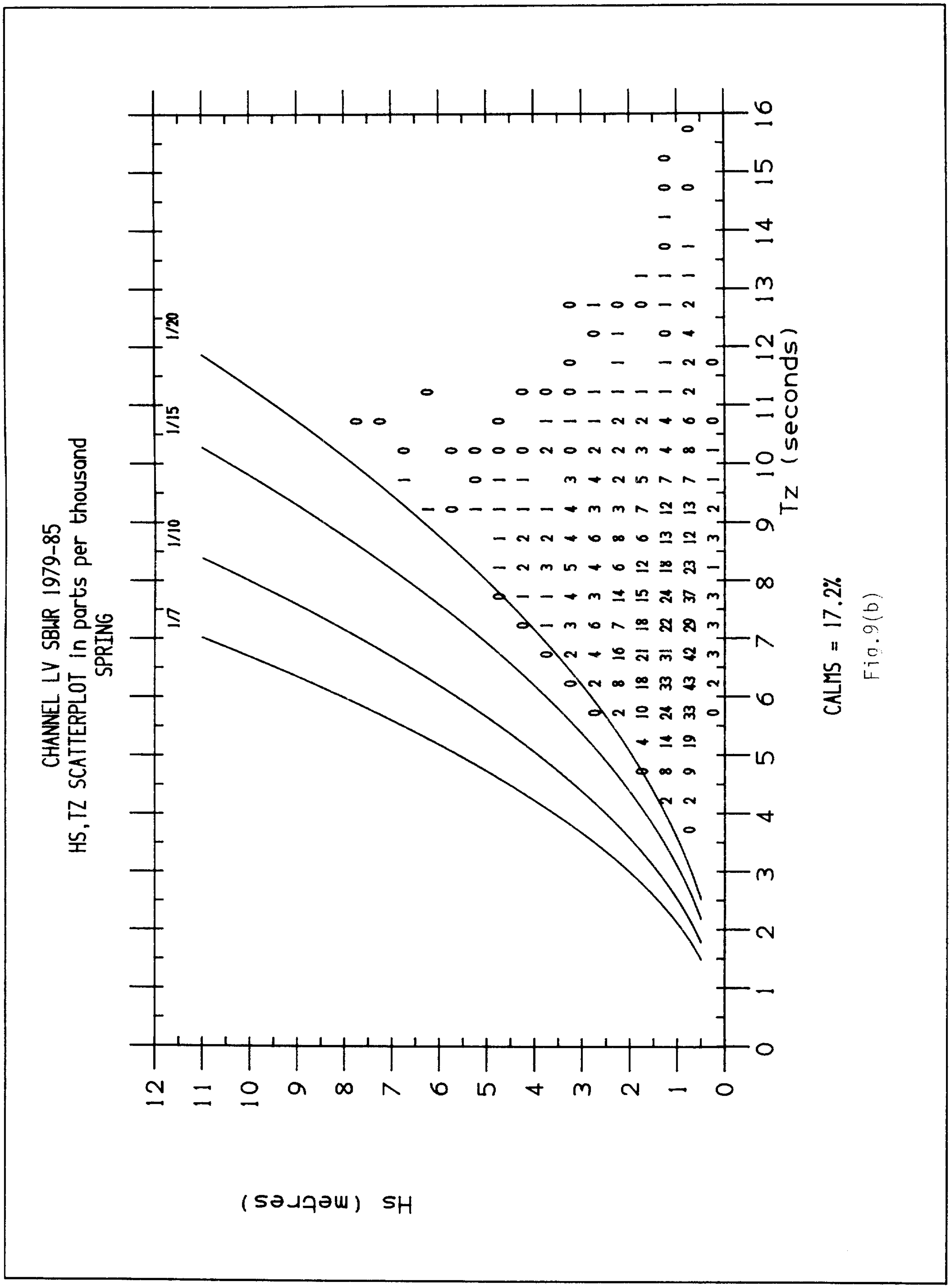
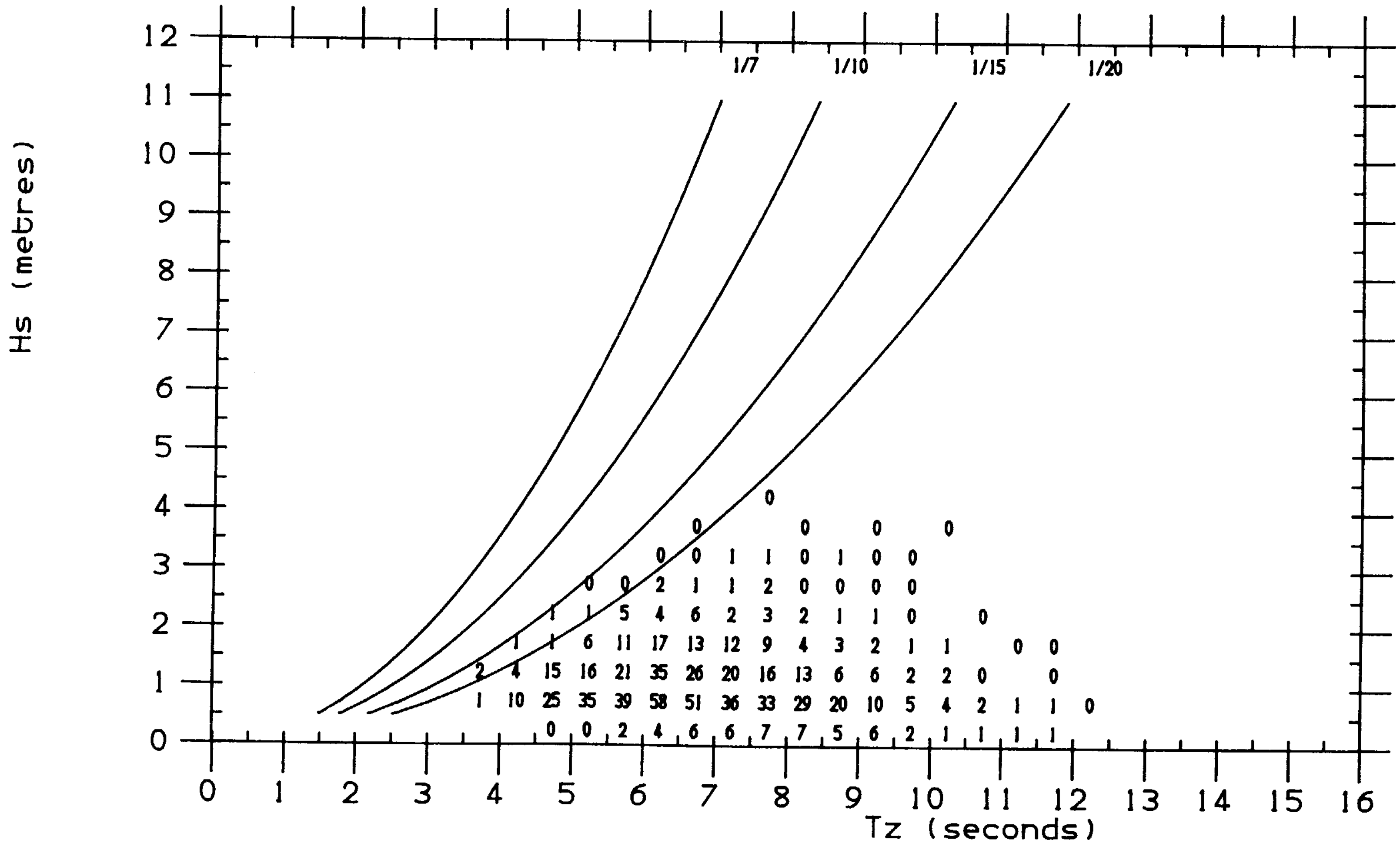

CHANNEL LV SBWR 1979-85
HS,TZ SCATTERPLOT in parts per thousand
SPRING
Hs (metres)
Tz (seconds)
1/7
1/10
1/15
1/20
CALMS = 17.2%

Fig.9(b)

CHANNEL LV SBWR 1979-85
HS,TZ SCATTERPLOT In parts per thousand
SUMMER



CALMS = 28.3%

Fig.9(c)

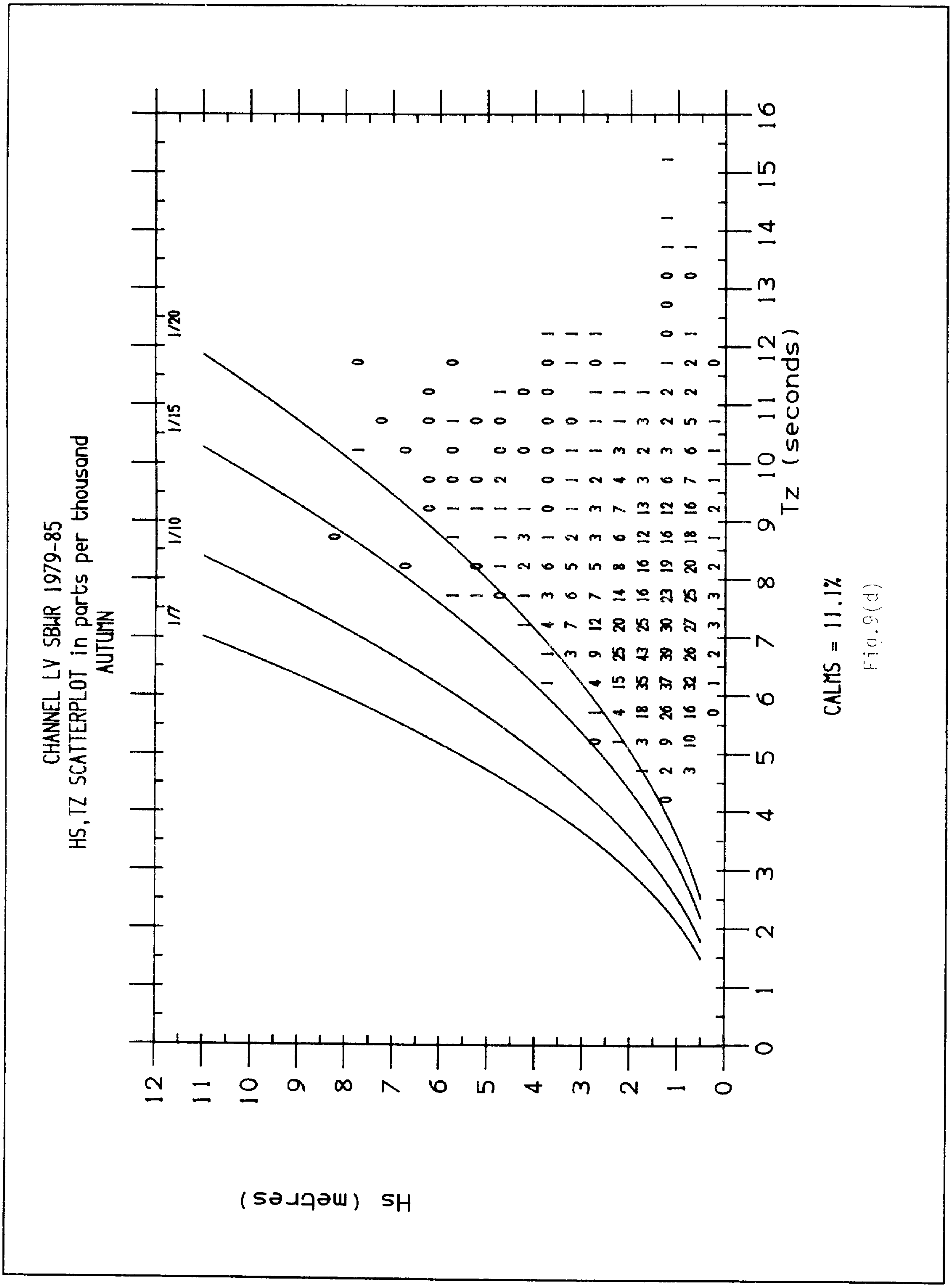

CHANNEL LV SBWR 1979-85
HS,TZ SCATTERPLOT in parts per thousand
AUTUMN
Hs (metres)
Tz (seconds)
1/7
1/10
1/15
1/20
CALMS = 11.1%

Fig.9(d)

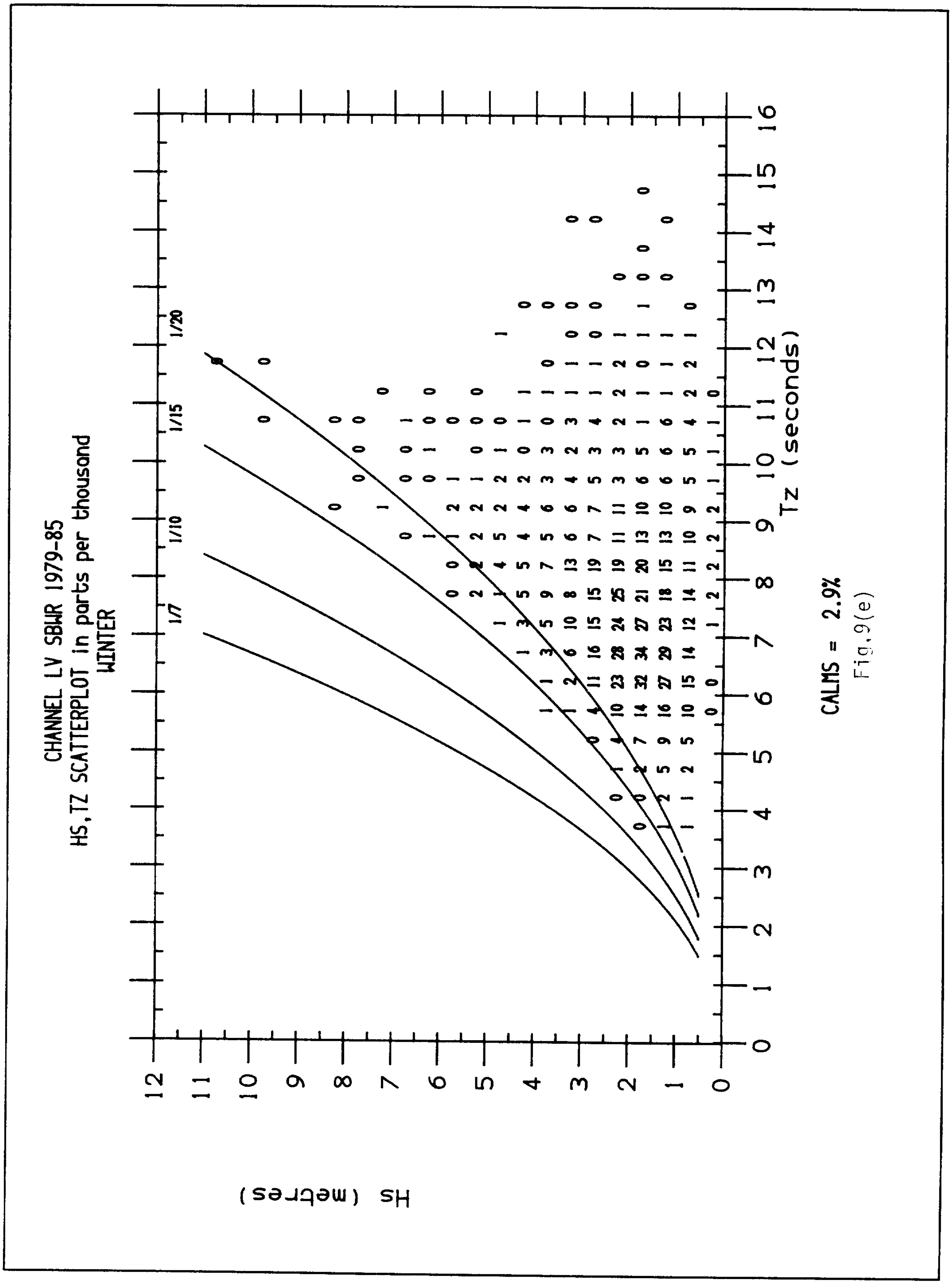
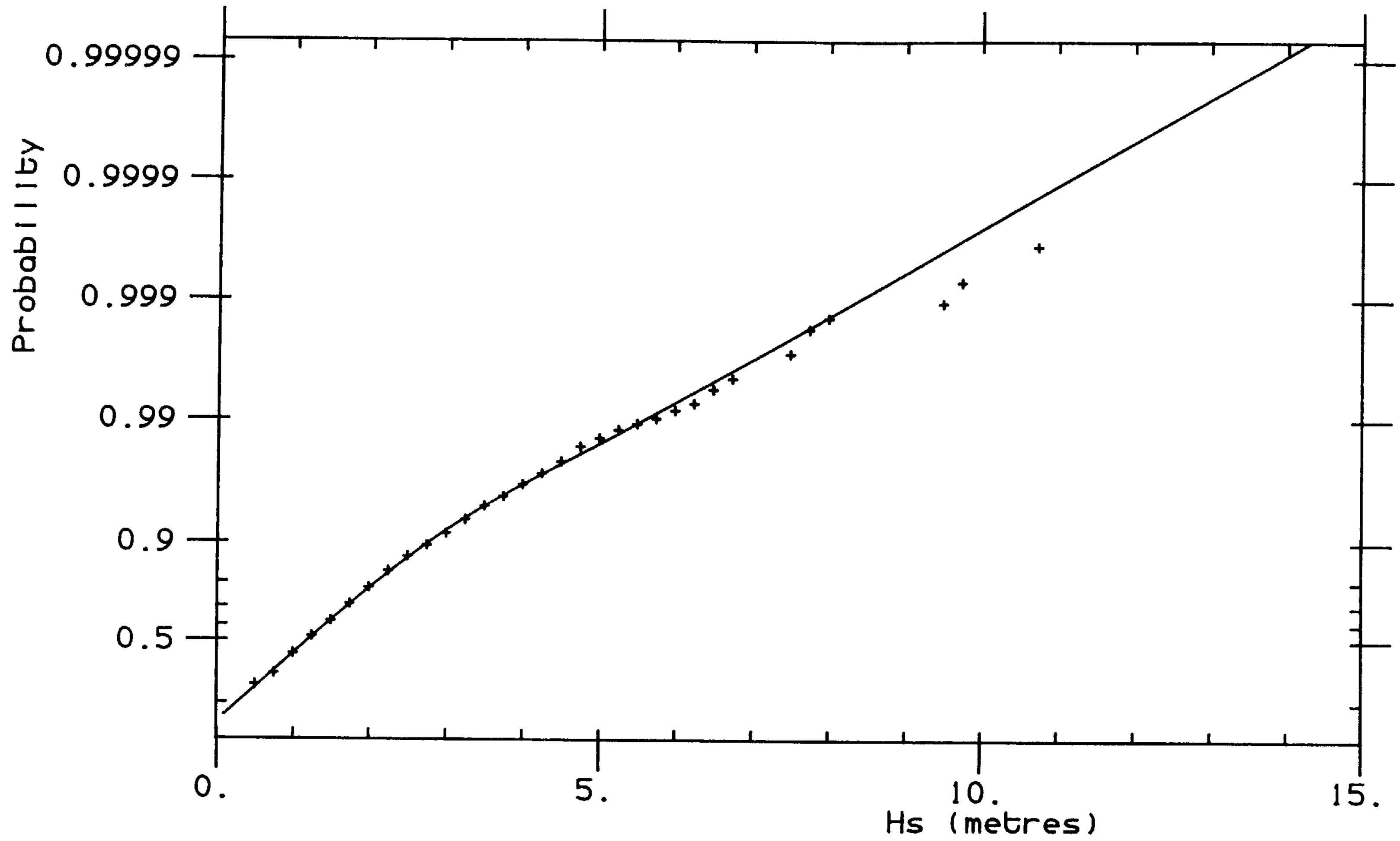

CHANNEL LV SBWR 1979-85
HS,TZ SCATTERPLOT in parts per thousand
WINTER
Hs (metres)
Tz (seconds)
1/7
1/10
1/15
1/20
CALMS = 2.9%

Fig.9(e)

CHANNEL LV SBWR 9:1979-8:1980
DOUBLE FT-1 PROBABILITY DISTRIBUTION



FRACTION 0.0231 A1,B1 0.8956 0.7492
A2,B2 4.5739 1.1969

Fig.10(a)

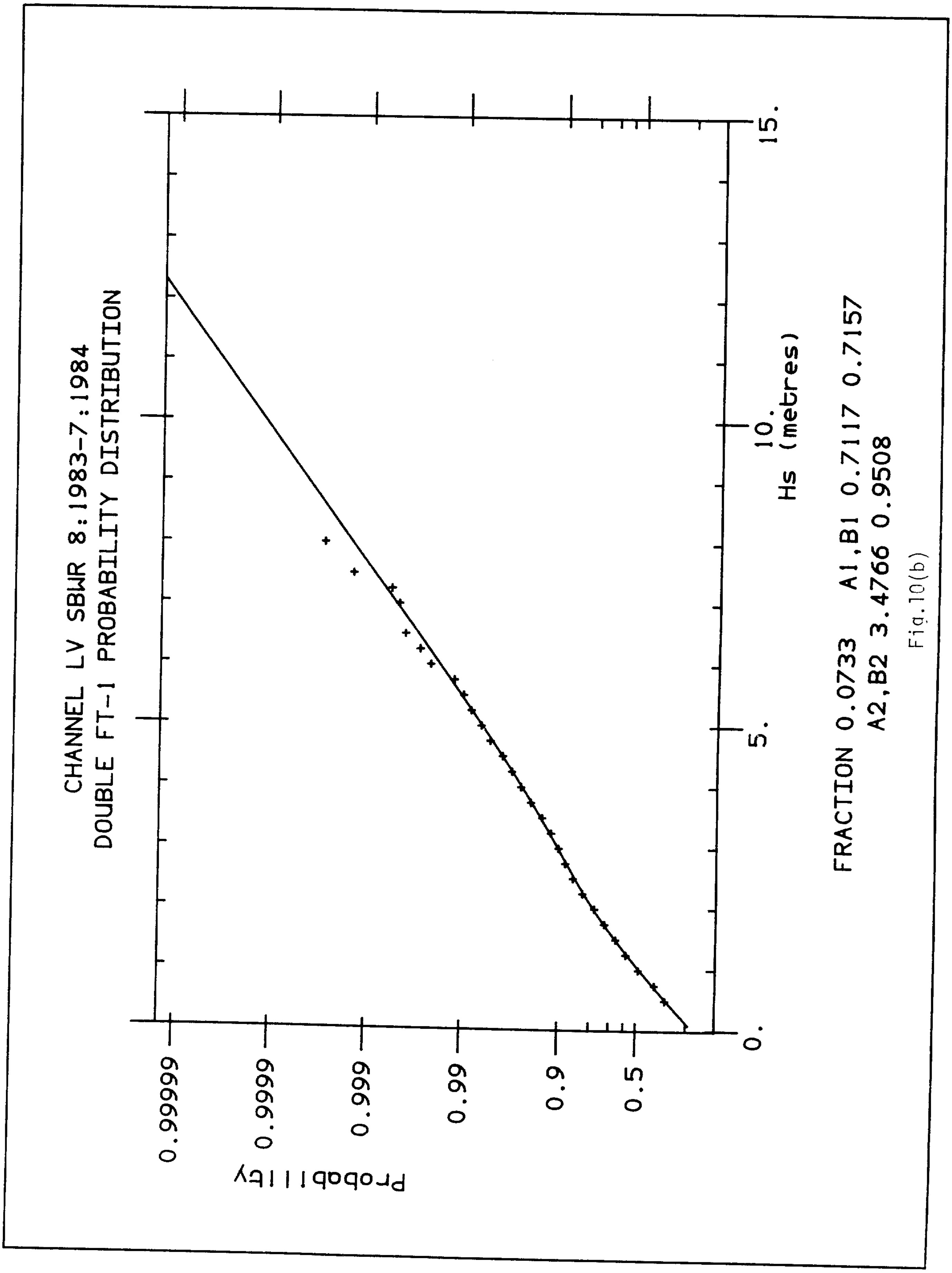
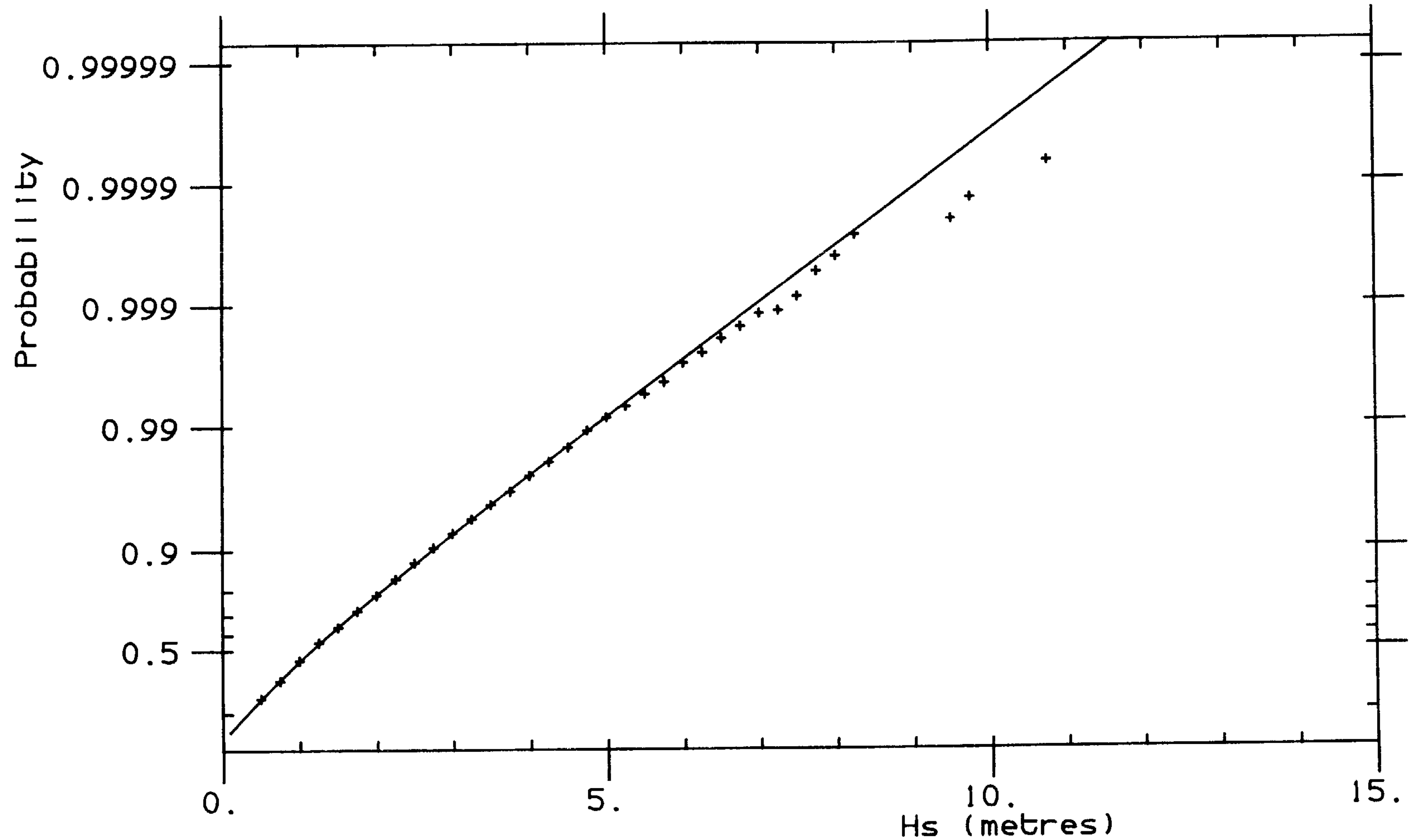

CHANNEL LV SBWR 8:1983-7:1984
DOUBLE FT-1 PROBABILITY DISTRIBUTION
Probability
0.99999
0.9999
0.999
0.99
0.9
0.5
0.
5.
10.
15.
Hs (metres)
FRACTION 0.0733 A1,B1 0.7117 0.7157
A2,B2 3.4766 0.9508

Fig.10(b)

CHANNEL LV SBWR 1979-85
DOUBLE FT-1 PROBABILITY DISTRIBUTION



FRACTION 0.2329 A1,B1 0.7298 0.5742
A2,B2 1.8662 0.9302

Fig.10(c)

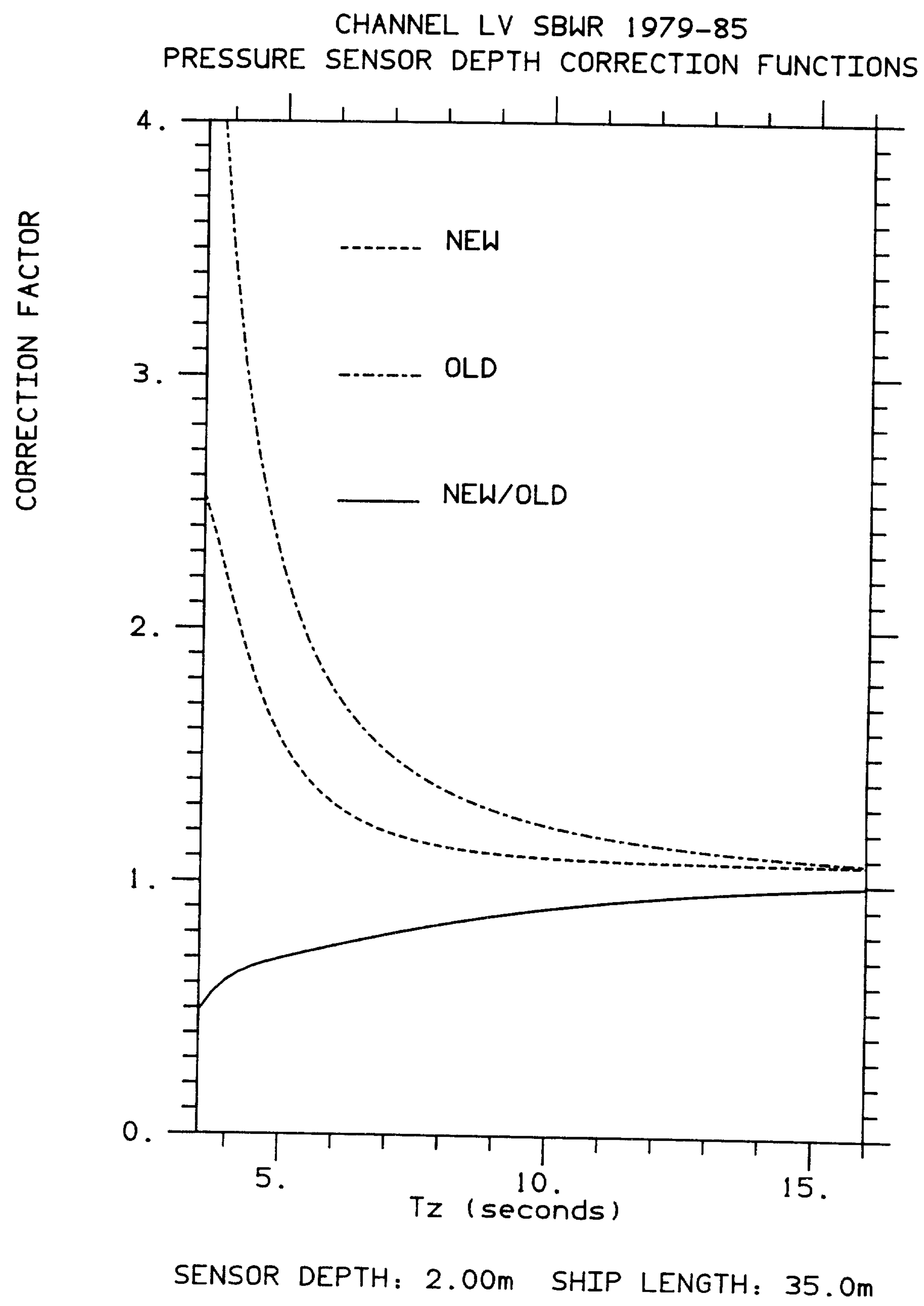

CHANNEL LV SBWR 1979-85
PRESSURE SENSOR DEPTH CORRECTION FUNCTIONS
CORRECTION FACTOR
4.
3.
2.
1.
0.
NEW
OLD
NEW/OLD
5.
10.
15.
Tz (seconds)
SENSOR DEPTH: 2.00m SHIP LENGTH: 35.0m

Fig.11

APPENDIX I

Chart Data Analysis Method and Correction Factors

The technique used to analyse the wave data was that proposed by Tucker (1961) and Draper (1963). A twelve minute record of sea surface elevation is taken once every three hours, and from this record are derived estimates of T_Z, the mean zero-up-crossing period, and of H_S, the significant wave height. The former is defined as the duration of the record divided by the number of zero-up-crossings; the latter is defined as 4σ, where σ is the standard deviation of the record, which is estimated from the number of zero-up-crossings, and from the size of the two highest crests and the two lowest troughs on the record. H_S as estimated by this method has a standard error of about 6%. The estimate of T_Z is a filtered over-estimate of the true T_Z and is close to the first moment period T_1; workers tend systematically to miss the smallest zero-up-cross waves on chart records.

The estimate of H_S obtained in this way must be corrected for the frequency response of the electronics of the system, and for the hydrodynamic attenuation of the pressure fluctuations, due to the pressure sensors being mounted in ports in the ship's hull some depth below the mean sea surface level.

The former correction, that for the frequency response of the system electronics, has the form given below; for further information see Crisp (1987).

$$C_E(\text{Mk.II}) = \{[(\omega_1^2 - \omega^2)^2 + \alpha_1^2\omega_1^2\omega^2][(\omega_2^2 - \omega^2)^2 + \alpha_2^2\omega_2^2\omega^2]\}^{\frac{1}{2}}\omega^{-4}$$

where $\omega_1 = 0.09498$
$\omega_2 = 0.10650$
$\alpha_1 = 1.916$
$\alpha_2 = 1.241$

The latter correction, that for the hydrodynamic attenuation of the pressure fluctuations, has in the past been modelled as a simple depth-dependent exponential, i.e.

$$C_H = \exp\{2.5\omega^2 d/g\}$$

However, Pitt (1988a) reports a new and much more satisfactory empirical form for C_H, which is described below, and has been applied to the data presented in this report. It was found possible to reconcile the different response functions returned from calibrations of SBWR's fitted to various ships of widely differing sizes by employing a Froude-type frequency scaling as

$$F = \left(\frac{2\pi}{g}\right)^{\frac{1}{2}} (Ld)^{\frac{1}{4}} f$$

where F is the scaled frequency variable based on frequency f ($=Tz^{-1}$), and L and d are the ship length and SBWR pressure sensor depth respectively. The empirical form found to give the most satisfactory fit to all measured response functions was a fourth-order polynomial in F, formulated as

$$R_H^2 = 1 - A_0\{1 - \exp[-A_1F - A_2F^2 - A_3F^4]\}$$

where $A_0 = 0.8468$
$A_1 = 0.4876$
$A_2 = -6.4058$
$A_3 = 26.6910$

This is the form of the new correction as applied to spectral estimates of H_S; when correcting Tucker-Draper estimates of H_S however, only one period parameter (T_Z) is available, which necessitates the application of a scalar correction, i.e. one evaluated at a single characteristic frequency (f_C), rather than a full correction separately evaluated at individual frequencies, as is possible with spectral data.

Pitt finds that the following form is necessary:

$$H_S = H_S' \left(\frac{Q(f_C)}{S_{SF}}\right)^{\frac{1}{2}}$$

where the characteristic frequency f_C is no longer T_Z^{-1}, but

$$f_C = \frac{1}{T_Z \times S_{T'T_Z}}$$

where $S_{T'T_Z}$ is an empirically determined constant relating the observed T_Z to the value of T_1 (the first moment period), found by Pitt to be the appropriate f_C to use in these circumstances. H_s and H_s' are the corrected and uncorrected values of H_s, respectively; and

$$Q(f_c) = C_E^2/R_H^2$$

A further empirical constant, S_{SF}, relates to the use of scalar rather than full correction, and is a factor based on comparison between scalar corrected spectral variance and fully corrected spectral variance. For Channel LV,

$$S_{T'Tz} = 1.1262$$

$$S_{SF} = 0.8741$$

See Fig. 11, which shows the old and new hydrodynamic correction factors, and the ratio of new to old, plotted as functions of T_Z. It can be seen that, for Channel LV, the old scheme over-estimated H_s, considerably so for low T_Z.

APPENDIX II

Method of System Calibration

Since there are two types of transducer in the shipborne wave recorder system, it is necessary to divide the calibration procedure into two sections. First the accelerometers are removed from the ship mountings and each is inserted into a rig which allows the transducer to be driven through a vertical circle of diameter 1 metre. The transducer is mounted in gimbals and maintains a vertical attitude during rotation. Two rotation rates are applied: 12 and 18 second periods which are derived from a crystal oscillator. The transducer is connected to the electronics unit in the usual way, and the calibration signal is displayed on the chart recorder. However, because a 1 metre 'heave' is small compared with the wave-heights usually experienced at sea, a precision amplifier (contained in the electronics) is switched into the circuit, converting the 1 metre into an apparent 10 metre signal. The output signal can then be read from the chart record and any corrections to instrument sensitivity made.

The pressure units cannot be easily subjected to a dynamic test since this requires the application of a sinusoidally-varying pressure. Therefore for routine re-calibration a static test is applied. Each pressure unit is fixed to the test rig and a series of discrete pressure levels is applied from a reservoir via a regulator valve. Each pressure level is set manually with the valve by reference to a precise pressure transducer contained within the calibrator unit. The output voltage of the transducer is monitored in the SBWR electronics unit and compared to the original laboratory calibration. Any changes in sensitivity are then compensated for by adjustment of the input amplifier gain.

Full calibrations are usually only possible when the ship comes into dock for its 3-yearly refit.

Monthly checks are made at sea by the lightvessel crews, who are asked to drain water through the valve assemblies to ensure that no blockage prevents the water pressure being transmitted to the pressure sensors, and then to take a test record, on a monthly basis. The test record consists of a short length of pen-trace with all transducers turned off (electrically), followed by a few minutes recording with each transducer on its own. The record thus produced shows two heave records (one from each accelerometer) which should look broadly similar; and also the pressure traces, which may not agree so well, but when compared with other monthly test records should exhibit no systematic error. These tests are not direct checks on calibration accuracy but are often good indicators of a fault condition developing.

APPENDIX III

Details of methods used for calculating 50-year return values

H_S is used as a measure of the "sea-state", (i.e., the intensity of wave activity) and is sampled every 3 hours. It is assumed that a set of H_S data for one year or more is representative of the wave climate.

For each binned data value of H_S, the probability that this value will not be exceeded is calculated; this probability is then plotted against H_S. The axes are scaled according to an appropriate distribution, so that data with a perfect fit would appear as a straight line on the diagram. In practice, the class of functions known as extreme-value distributions are often found to give a close fit to the data. It should be noted that these functions are used only as 'templates' and not strictly as extreme-value distributions. These functions describe independent random data only, which climatic data are not, given 3-hourly data records and weather-system time-scales ranging from hours to years, etc.

FORMULAE

(i) Weibull (3-parameter)

$$\text{Prob } (H_S \le h) = \begin{cases} 1 - \exp\{-(\frac{h-A}{B})^C\}, & \text{for } h>A \\ 0 & \text{, for } h\le A \end{cases}$$

(ii) Weibull (2-parameter)

$$\text{Prob } (H_S \le h) = \begin{cases} 1 - \exp\{-(\frac{h}{B})^C\}, & \text{for } h>0 \\ 0 & \text{, for } h\le 0 \end{cases}$$

(iii) Fisher-Tippett I

$$\text{Prob } (H_S \le h) = \exp[-\exp\{-(\frac{h-A}{B})\}], \text{ where } B>0$$

In each case, A is the location parameter, B is the scale parameter, C is the shape parameter. The Weibull 2-parameter distribution is the Weibull 3-parameter distribution with $A = 0$.

For each distribution, the best fit straight line is drawn, then extrapolated to some desired probability and the corresponding value of H_s read off as the "design sea-state".

FITTING OF DISTRIBUTIONS BY THE METHOD OF MOMENTS

Fitting the Fisher-Tippett I Distribution

The mean and variance of this distribution are $A + \gamma B$ and $\pi^2 B^2/6$ respectively, where γ (Euler's constant) = 0.5772...; so the moments estimators given data X_i, $1 \le i \le n$, are given by

$$\tilde{A} = \bar{x} - \gamma \tilde{B}$$

$$\tilde{B} = \sqrt{6}\, s/\pi$$

where

$$\bar{x} = \Sigma\, x_i/n$$

$$s^2 = \sum_i (x_i - \bar{x})^2/(n - 1)$$

and values of $\bar{x}$ and s^2 may be estimated from grouped data.

Fitting the Weibull 2-parameter Distribution

The probability distribution function for the 2-parameter Weibull distribution is

$$P_X(x) = \frac{c}{B} \left(\frac{x}{B}\right)^{c-1} \exp[-(x/B)^c] \qquad (3.1)$$

This usually is fitted only to the upper tail of the data, above some specified level x_0; this can be done by defining 'partial' moments about the origin of values above x_0 such that

$$\nu_\gamma = \int_{x_0}^{\infty} x^\gamma p_X(x)\, dx \qquad (3.2)$$

and substituting for $p_X(x)$ from 3.1 for γ=1 and 2 leads to

$$\nu_1 = \frac{x_0}{Z^Y} \Gamma(1 + Y, Z)$$
$$(3.3)$$
$$\nu_2 = \frac{x_0}{Z^Y} \Gamma(1 + 2Y, Z)$$

where $Y = {}^1/C$ and $Z = (x_0/B)^C$.

and $\Gamma(p,D) = \int_D^{\infty} y^{p-1}\, e^{-y}\, dy$

Therefore given estimates of ν_1 and ν_2 from data using equation 3.2 and a value for the lower limit of data to be fitted x_0, then estimates of Y and Z, and hence of B and C can be obtained by numerical solution of 3.3.

Fitting the Weibull 3-parameter Distribution

The Weibull 3-parameter distribution can be converted to the 2-parameter by the transformation $y = x - A$. The mean and variance of the 2-parameter distribution are given by

$$\bar{x} = B\Gamma(1 + \frac{1}{C}) \qquad (3.4)$$

$$s^2 = B^2\{\Gamma(1 + \frac{2}{C}) - \Gamma^2(1 + \frac{1}{C})\}$$

$$= \bar{x}^2\{\frac{\Gamma(1 + \frac{2}{C})}{\Gamma^2(1 + \frac{1}{C})} - 1\} \qquad (3.5)$$

Values of x and s^2 may be estimated from grouped data; the moments estimator for

C can be found by numerical solution of 3.5; C can then be substituted into 3.4 to provide B. An initial guess is entered first for A, and the best solution for all parameters is found by iteration to obtain the minimum χ^2 distribution.

FITTING OF FT-1 DISTRIBUTION BY MAXIMUM LIKELIHOOD

The FT-1 distribution is fitted by maximum likelihood to monthly maxima. For data x_i, $1 \le i \le n$, the maximum likelihood estimators for A and B are found from

$$\hat{A} = -\hat{B}\log\left[\frac{1}{n}\sum_{i=1}^{n} e^{-x_i/\hat{B}}\right]$$

$$\hat{B} = \frac{1}{n}\sum_{i=1}^{n} (x_i - \hat{A})(1 - \exp\{-[x_i - \hat{A}]/\hat{B})$$

See Johnson & Kotz (1970); these equations are solved by iteration, with initial estimates for A and B provided by their moments estimators.

Monthly maxima were fitted in calendar months to FT1 distributions to obtain the fifty-year value of H_s. The annual probability distribution P_{ANN} was found by combining the individual calendar monthly distributions P_M as

$$P_{ANN}\ (H_s \le h) \quad = \prod_{M=1}^{12} P_M(H_s \le h) \qquad (1)$$

where

$$P_M(H_s \le h) \quad = \exp\{-\exp(-[h-A_M]/B_M)\} \qquad (2)$$

The fifty-year return value of H_s was found by solving equation 1 for $h = H_s(50)$ and for $P_{ANN} = 0.98$.

CALCULATION OF 50-YEAR RETURN VALUE

The 50-year return value of H_s is defined as that value of H_s which is exceeded on average once in 50 years. In each case this has been determined by extrapolating the relevant distribution to the required probability of exceedance which is determined by assuming some frequency of observation (taken in this report to be 3-hourly), and by assuming all H_S observations to be independent.

The 50-year return value of H_S, $H_S(50)$ is then given by

$$\text{Prob }(H<H_S(50)) = 1 - \frac{1}{50 \times 365.25 \times 8}$$
$$= 0.99999316$$

Fitting to seasonal or monthly data reduces the number of days observation per year from 365.25 to 365.24/4 or 365.25/12 respectively, and reduces the relevant probabilities to 0.99997262 and 0.99991786 respectively.

For fitting to invididual calendar monthly maxima,

$$\text{Prob}(H<H_S(50)) = 1 - \frac{1}{50} = 0.98$$