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# WAVES RECORDED AT DOWSING LIGHT VESSEL 1970 – 1985

BY

S. BACON

REPORT NO. 262

1989

Natural Environment Research Council

INSTITUTE OF
OCEANOGRAPHIC SCIENCES
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# INSTITUTE OF OCEANOGRAPHIC SCIENCES

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# Waves Recorded at Dowsing Light Vessel 1970-1985

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# DOCUMENT DATA SHEET

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*ABSTRACT*


Measurements of waves have been made routinely at Dowsing Light Vessel using a Shipborne Wave Recorder from 1970 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 $H_s$. 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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CONTENTS

## 1. INTRODUCTION

Wave measurements were recorded routinely off the mouth of the Humber estuary at Dowsing Light Vessel from 1970 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. Wave climate information, as derived from these parameters, is presented.

## 2. LOCATION

The site at which the wave measurements were taken is shown on the map in Figure 1. It is approximately 48 kilometres east of Spurn Point on the east coast of England, at position 53°34.0'N, 000°50.2'E, where the water depth is about 26 metres; however the sea-bed in the vicinity is very irregular, and several shoals are charted with water depths above them of between 6 and 20 metres. The site is open to winds from between NW through N to E; there is a complex series of banks from between E to SSE, and from SSE to NW, the land is between 30 and 60 n.m. distant.The tidal currents in the area are quite strong, the maximum current being generally about 2 knots (1 metre/sec), with directions of approximately 150° and 330°. Due to the shoals around the vessel the currents may be even stronger locally, and may occasionally cause either a real or an apparent increase in the steepness of the waves to an unusually high level. This effect would be most pronounced for short, low-period waves.

## 3. MEASUREMENT AND RECORDING SYSTEMS

Dowsing Light Vessel (LV) was fitted with a Shipborne Wave Recorder (SBWR) of Mark I up to the 1981 LV refit, and of Mark II thereafter; see Tucker (1956) for a description of the SBWR Mark I, and Haine (1980) for the Mark II. The instruments provide 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 (1988) 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 Dowsing, the pressure sensor is not deep mounted so any alterations over the original correction scheme are small; however, results reported here differ to some extent from those from previous reports of data from Dowsing LV (Draper 1976, Fortnum 1981). A comparison of the two correction schemes is presented in Appendix I. Note that the pressure sensor was deeper mounted (1.46m) during 1970-71 than subsequently (0.88m). The length of the LV is 35 metres.

## 4. MAINTENANCE AND CALIBRATION

A summary of the history of SBWRs on Dowsing LV is given below, and a description of the calibration method is given in Appendix II. Calibrations were carried out by IOSDL staff. Up to 1981, a 4753 (valve type, or Mk.I) SBWR was deployed on the Light Vessel. Thereafter, a 5254 (solid state type, or Mk.II) was deployed.

May 1970: Instrument was overhauled and re-calibrated whilst the vessel was in dry dock at South Shields. Pressure sensor depth was 1.46 m.

October 1971: Repair and re-calibration of equipment were carried out following a report of an intermittent fault. The re-calibration showed that there had been a change in sensitivity of -5.6% (i.e. the accelerometers were under-reading the waves by this amount). It was not possible to find out whether the replacement component had contributed to this change, and therefore it was assumed that all data recorded up to the time of the intermittent fault were acceptable.

September-October 1975: A replacement Mk.I wave recorder was installed during the vessel's refit. Pressure sensor depth now is 0.88m.

May-June 1977: A re-calibration was carried out during the vessel's refit, and the change in sensitivity was found to be -3.2%. The Light Vessel returned to Dowsing station on 23 September 1977.

October 1981: A calibration was carried out when the vessel came off station, and the change in sensitivity was found to be +9.4%. It has been assumed that the change was linear with time.

January 1982: Vessel returned to station, having been fitted with a Mk.II SBWR.

April 1985: SBWR re-calibrated during refit; change in sensitivity found to be negligible.

## 5. WAVE DATA COVERAGE

The total data return, and the data return per season, where the seasons are defined as follows, are given below.

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

| | | |
|---|---|---|
| Total number of valid records: | | 27377 |
| Total from | Spring: | 6076 |
| | Summer: | 6743 |
| | Autumn: | 7458 |
| | Winter: | 7100 |

Returns for each month are given in Table 1. 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 1 foot or 0.3 m (1981 and before) or 0.5 m (1982 and after). The change in definition arose after the 1981 LV refit, when the SBWR Mk.II was fitted, along with differently scaled chart records. This has given rise to a large apparent change in the number of calms recorded, as a fraction of total. This is discussed further in Appendix IV. As a consequence of the discussion therein, $H_s$ (calm) is set to $0 < H_s$ (calm) $\leq 0.5$ m for data grouped in 0.5 m bins, and $H_s$ (calm) = 0.25 m for individual record calculations (e.g. monthly mean).

## 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 Dowsing occurred on 15 February 1979 at 0900 hours with $H_s$ = 6.29 m and associated $T_z$ = 9.73s. The second highest value occurred during a separate storm in the following month of the same year (6.05m, 1800 hours 16 March 1979, $T_z$ = 8.77s).

Estimates of the probability distributions of $H_s$ are shown in Figure 2 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 3. 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.

Evidence was sought for the presence of trends in the data, firstly by fitting a seasonal sine curve with a mean trend to the time series of all monthly values; and secondly by examining the time series of values for individual calendar months (i.e. all Januaries, etc.). In neither case was any significant trend found. However, it is evident from the data that there was a peak in 'activity' around 1979 and 1980; for example, the highest monthly mean values of $H_S$ occurred in February 1979, March 1979, May 1980, July 1980, September 1978, October 1980, November 1980, December 1978. This is reflected also in the other measures of $H_S$ by month.

Rye (1976) in a paper entitled 'Changes in North Sea Climate' reported an estimated 3-4% increase per year in severity of wave conditions, based on visual wave height observations for the rescue ship 'Famita' at 57.5N 3.0E between the years 1959-73. It is possible that the suggested peak in severity of wave conditions around 1979-80 represents a turning point for this trend.

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 4, 5 and 6 show the cumulative probability distribution of all $H_s$ data and (respectively) the fitted FT1, 3- and 2-parameter Weibull distributions.

The FT1 distribution, fitted by method of moments to all data and by maximum likelihood to monthly maxima, gives similar values in each case for $H_s(50)$, 8.23m and 8.31m respectively. Note that when fitting monthly maxima, monthly values with >20% missing data were not included. The parameters of the FT-1 distributions estimated by fitting to monthly maxima are given in Table 4b. The 2-parameter Weibull distribution is fitted to data above 2.5m only (approximately 10% of total) since it provides a very poor fit to the whole data set. The 3-parameter Weibull distribution is fitted by a combination of the method of moments and minimum $\chi^2$; the resulting value of $H_s(50)$, 6.70m, is low, but it can be seen that the fit 'misses' the tail and underestimates consequently. Eight values of annual maximum $H_s$ were extracted from the data for fitting by maximum likelihood to the FT1 distribution. The results are quoted for interest ($H_s(50)$ = 6.70m), but the inaccuracy consequent on estimating two parameters from only eight data values is reflected in the 90% confidence limits, calculated as in Challenor (1979), 6.1m $\leq H_s(50) \leq$ 8.7 m.

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 7, 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 6 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 $H_s$ were (2.4, 1.6), (1.6, 2.7), (2.2, 4.5) and (1.1, 3.1) metres, start and end values respectively. Therefore, if required, the data may be 'differenced' back into non-cumulative form with little loss of accuracy; 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 = 0.343, or ~35%.

(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 35.8; probability x number of events = 12.3 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, 16.2% of total time finds $H_s \geq 2$ m, or a little over 59 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 $\geq 6$) = 0.576, prob($H_s \geq 4$; duration $\geq 9$) = 0.333; so prob ($H_s \geq 4$; duration=6) = 0.576-0.333 = 0.243.

## 7.2 Statistics of zero-up-crossing period

Estimates of the probability distributions of $T_z$ are included in Figure 2; 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 1 March 1984 at 2100 hours with $T_z$ = 10.00s and associated $H_s$ = 1.08 m.

## 7.3 Statistics of the joint distribution of $H_s$ and $T_z$

Figure 8 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.

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## TABLE 1
### Monthly Data Returns

| Year | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1970 | - | - | - | - | 206* | 229 | 248 | 246 | 240 | 245 | 240 | 242 |
| 1971 | 244 | 224 | 247 | 231 | - | - | - | - | - | - | - | - |
| 1975 | - | - | - | - | - | - | - | - | - | - | 240 | 248 |
| 1976 | 247 | 232 | 248 | 240 | 248 | 240 | 247 | 248 | 240 | 248 | 240 | 248 |
| 1977 | 248 | 224 | (90) | - | - | - | (67) | 247 | 240 | 248 | 227 | 238 |
| 1978 | 242 | 224 | 247 | 239 | 249 | 237 | 245 | 247 | 239 | 248 | 240 | 246 |
| 1979 | 248 | 224 | 248 | 210* | 244 | 240 | 247 | 224 | 240 | 242 | 240 | 248 |
| 1980 | 247 | 232 | 240 | 236 | 238 | 240 | 247 | 243 | 237 | 242 | 239 | 247 |
| 1981 | 244 | 224 | 247 | 228 | 242 | (106) | - | - | - | - | - | - |
| 1982 | (121) | 223 | (138) | 240 | 248 | 234 | 242 | 246 | 240 | 248 | 237 | 240 |
| 1983 | - | - | - | (100) | 246 | 239 | 241 | 243 | 238 | 248 | 236 | 248 |
| 1984 | 246 | 230 | 243 | 240 | 245 | 237 | 240 | 243 | 240 | 235 | 233 | 242 |
| 1985 | 246 | (35) | - | - | - | (29) | 246 | 247 | 240 | 248 | 240 | 248 |

## TABLE 2
### Monthly Calm Returns

| Year | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1970 | - | - | - | - | 6* | 9 | 33 | 12 | 27 | 4 | 0 | 0 |
| 1971 | 0 | 0 | 0 | 0 | - | - | - | - | - | - | - | - |
| 1975 | - | - | - | - | - | - | - | - | | - | 0 | 0 |
| 1976 | 0 | 0 | 0 | 2 | 8 | 29 | 0 | 6 | 0 | 0 | 0 | 0 |
| 1977 | 0 | 0 | (0) | - | - | - | (0) | 15 | 0 | 0 | 0 | 0 |
| 1978 | 0 | 0 | 0 | 0 | 4 | 21 | 13 | 4 | 0 | 21 | 0 | 0 |
| 1979 | 0 | 0 | 0 | 8* | 14 | 1 | 0 | 5 | 1 | 0 | 0 | 0 |
| 1980 | 0 | 6 | 0 | 7 | 8 | 27 | 5 | 10 | 7 | 0 | 0 | 0 |
| 1981 | 0 | 1 | 0 | 10 | 11 | (2) | - | - | - | - | - | - |
| 1982 | (34) | 34 | (44) | 68 | 87 | 96 | 73 | 70 | 103 | 67 | 21 | 22 |
| 1983 | - | - | - | (2) | 70 | 51 | 128 | 81 | 48 | 17 | 35 | 2 |
| 1984 | 0 | 39 | 19 | 75 | 32 | 59 | 68 | 109 | 1 | 30 | 1 | 26 |
| 1985 | 0 | (6) | - | - | - | (3) | 4 | 15 | 20 | 28 | 0 | 0 |

**TABLE 3A**

**$H_S$ Histogram values (% occurrence)**

| Data Period | Calms | Bin Upper Limit (m) 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| All | 7.56 | 5.72 | 27.49 | 26.94 | 16.10 | 8.81 | 4.12 | 1.86 | 0.72 | 0.32 | 0.21 | 0.08 | 0.05 | 0.02 |
| Spring | 7.69 | 5.47 | 27.59 | 29.82 | 16.31 | 7.89 | 3.02 | 1.02 | 0.54 | 0.26 | 0.29 | 0.07 | 0.02 | 0.02 |
| Summer | 14.10 | 12.79 | 37.19 | 22.91 | 7.98 | 3.59 | 1.13 | 0.20 | 0.10 | | | | | |
| Autumn | 5.89 | 2.79 | 24.36 | 28.41 | 18.83 | 10.59 | 5.43 | 2.32 | 0.80 | 0.40 | 0.11 | 0.07 | 0.01 | |
| Winter | 2.44 | 1.70 | 20.67 | 26.62 | 21.43 | 13.28 | 6.97 | 3.96 | 1.47 | 0.62 | 0.43 | 0.21 | 0.18 | 0.04 |

**TABLE 3B**

**$T_Z$ Histogram values (% occurrence)**

| Data Period | Bin Upper Limit (s) 3.0 | 3.5 | 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 | 10.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| All | 0.39 | 3.51 | 8.86 | 12.73 | 15.03 | 15.11 | 13.48 | 10.76 | 6.33 | 3.47 | 1.80 | 0.66 | 0.20 | 0.08 | 0.01 | |
| Spring | 0.50 | 4.02 | 8.77 | 12.26 | 16.14 | 15.03 | 13.54 | 10.21 | 5.79 | 3.44 | 1.72 | 0.65 | 0.15 | 0.07 | 0.00 | 0.02 |
| Summer | 0.54 | 4.37 | 11.38 | 13.06 | 12.83 | 12.20 | 11.76 | 9.65 | 5.61 | 2.89 | 1.33 | 0.20 | 0.03 | 0.05 | 0.01 | |
| Autumn | 0.16 | 2.88 | 8.04 | 13.51 | 15.88 | 17.02 | 13.30 | 10.17 | 6.48 | 3.49 | 1.95 | 0.95 | 0.24 | 0.04 | 0.01 | |
| Winter | 0.36 | 2.77 | 7.20 | 12.08 | 15.29 | 16.24 | 15.37 | 13.05 | 7.48 | 4.09 | 2.22 | 0.85 | 0.39 | 0.16 | 0.01 | |

**TABLE 4A**

**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 | 8.23 | 0.93 | 0.61 | - |
| | Spring | 6.91 | 0.91 | 0.57 | - |
| | Summer | 5.35 | 0.64 | 0.45 | - |
| | Autumn | 7.41 | 1.06 | 0.60 | - |
| | Winter | 8.23 | 1.23 | 0.67 | - |
| | May 70-Apr 71 | 7.66 | 0.91 | 0.57 | - |
| | Nov 75-Oct 76 | 7.43 | 0.89 | 0.55 | - |
| | 1978 | 8.23 | 1.06 | 0.60 | - |
| | 1979 | 9.26 | 1.02 | 0.69 | - |
| | 1980 | 8.57 | 1.08 | 0.63 | - |
| | 1982 | 7.85 | 0.72 | 0.60 | - |
| | 1984 | 8.18 | 0.90 | 0.61 | - |
| | Monthly maxima | 8.31 | (see A.III and section 8) | | |
| | Annual maxima | 6.70 | (see A.III and section 8) | | |
| Weibull 2-parameter | All above 2.5m | 7.49 | - | 1.25 | 1.38 |
| Weibull 3-parameter | All | 6.76 | 0.17 | 1.25 | 1.49 |

**TABLE 4B**

**50-Year Return Values of $H_S$**

Fisher-Tippett Type I fitted to Monthly Maxima

| Month | $H_S(50)$ (m) | A(location) (m) | B(Scale) (m) |
|---|---|---|---|
| 1 | 7.55 | 3.84 | 0.95 |
| 2 | 6.96 | 3.49 | 0.89 |
| 3 | 6.95 | 3.76 | 0.82 |
| 4 | 5.75 | 3.27 | 0.64 |
| 5 | 3.88 | 2.79 | 0.28 |
| 6 | 4.00 | 2.20 | 0.46 |
| 7 | 4.85 | 2.23 | 0.67 |
| 8 | 4.73 | 2.81 | 0.49 |
| 9 | 4.33 | 3.01 | 0.34 |
| 10 | 6.19 | 3.47 | 0.70 |
| 11 | 6.10 | 3.64 | 0.63 |
| 12 | 6.42 | 4.16 | 0.57 |

**TABLE 5**

**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 | 7.49E-1 | 4.97E-1 | 3.60E-1 | 2.77E-1 | 2.34E-1 | 1.96E-1 | 1.55E-1 | 1.38E-1 | 1.15E-1 |
| 2.5 | 1.0 | 7.03E-1 | 4.02E-1 | 2.81E-1 | 2.06E-1 | 1.78E-1 | 1.48E-1 | 1.15E-1 | 8.07E-2 | 7.17E-2 |
| 3.0 | 1.0 | 6.48E-1 | 3.43E-1 | 2.21E-1 | 1.67E-1 | 1.37E-1 | 1.16E-1 | 8.96E-2 | 7.46E-2 | 5.97E-2 |
| 3.5 | 1.0 | 4.84E-1 | 2.90E-1 | 1.87E-1 | 1.35E-1 | 1.16E-1 | 9.03E-2 | 7.74E-2 | 7.74E-2 | 7.10E-2 |
| 4.0 | 1.0 | 5.76E-1 | 3.33E-1 | 2.58E-1 | 1.82E-1 | 1.36E-1 | 1.21E-1 | 7.58E-2 | 6.06E-2 | 4.55E-2 |
| 4.5 | 1.0 | 5.75E-1 | 3.25E-1 | 1.50E-1 | 1.50E-1 | 1.25E-1 | 1.25E-1 | 5.00E-2 | 2.50E-2 | 2.50E-2 |
| 5.0 | 1.0 | 6.32E-1 | 3.16E-1 | 2.11E-1 | 2.11E-1 | 1.05E-1 | 1.05E-1 | 1.05E-1 | - | - |
| 5.5 | 1.0 | 4.00E-1 | 3.00E-1 | 2.00E-1 | 1.00E-1 | - | - | - | - | - |
| 6.0 | 1.0 | - | - | - | - | - | - | - | - | - |

| $H_S$ threshold (m) | Least Duration (Hours) 33 | 36 | 39 | 42 | 45 | 48 | 51 | 54 | 57 | 60 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2.0 | 1.01E-1 | 8.53E-2 | 7.32E-2 | 6.20E-2 | 5.25E-2 | 4.31E-2 | 3.45E-2 | 2.84E-2 | 2.67E-2 | 2.58E-2 |
| 2.5 | 6.28E-2 | 4.93E-2 | 3.89E-2 | 3.29E-2 | 2.84E-2 | 2.54E-2 | 2.24E-2 | 1.94E-2 | 1.79E-2 | 1.49E-2 |
| 3.0 | 5.37E-2 | 5.08E-2 | 4.18E-2 | 3.58E-2 | 2.69E-2 | 2.39E-2 | 1.79E-2 | 1.49E-2 | 1.49E-2 | 1.49E-2 |
| 3.5 | 4.52E-2 | 4.52E-2 | 3.87E-2 | 3.23E-2 | 2.58E-2 | 2.58E-2 | 1.94E-2 | 1.94E-2 | 1.94E-2 | 1.94E-2 |
| 4.0 | 4.55E-2 | 4.55E-2 | 3.03E-2 | 3.03E-2 | 3.03E-2 | 3.03E-2 | 3.03E-2 | 3.03E-2 | 3.03E-2 | 3.03E-2 |
| 4.5 | 2.50E-2 | 2.50E-2 | 2.50E-2 | 2.50E-2 | 2.50E-2 | 2.50E-2 | 2.50E-2 | 2.50E-2 | 2.50E-2 | - |

TABLE 5 (Continued)

Persistence of 'Storms' of $H_S$

| $H_S$ threshold | Least Duration (Hours) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (m) | 63 | 66 | 69 | 72 | 75 | 78 | 81 | 84 | 87 | 90 |
| 2.0 | 2.35E-2 | 1.98E-2 | 1.72E-2 | 1.46E-2 | 1.46E-2 | 1.21E-2 | 1.12E-2 | 1.03E-2 | 7.75E-3 | 6.03E-3 |
| 2.5 | 1.35E-2 | 1.20E-2 | 1.05E-2 | 7.47E-3 | 5.98E-3 | 4.48E-3 | 4.48E-3 | 4.48E-3 | 2.99E-3 | 2.99E-3 |
| 3.0 | 1.49E-2 | 5.97E-3 | 5.97E-3 | 5.97E-3 | 5.97E-3 | 5.97E-3 | 5.97E-3 | 5.97E-3 | 2.99E-3 | - |
| 3.5 | 1.29E-2 | 1.29E-2 | 1.29E-2 | 1.29E-2 | 6.45E-3 | 6.45E-3 | 6.45E-3 | - | - | - |
| 4.0 | 3.03E-2 | 3.03E-2 | 3.03E-2 | - | - | - | - | - | - | - |

| $H_S$ threshold | Least Duration (Hours) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (m) | 93 | 96 | 99 | 102 | 105 | 108 | 111 | 114 | 117 | 120 |
| 2.0 | 5.17E-3 | 3.45E-3 | 3.45E-3 | 3.45E-3 | 3.45E-3 | 3.45E-3 | 2.58E-3 | 2.58E-3 | 2.58E-3 | 2.58E-3 |
| 2.5 | 2.99E-3 | 2.99E-3 | 2.99E-3 | 2.99E-3 | 2.99E-3 | 2.99E-3 | 1.49E-3 | 1.49E-3 | 1.49E-3 | 1.49E-3 |

TABLE 6

**Individual $H_S$ 'storm' Outliers**

| $H_S$ threshold (m) | Duration (hours) |
|---|---|
| 2.0 | 124.5 |
| 2.0 | 127.6 |
| 2.0 | 169.4 |
| 2.5 | 157.9 |

TABLE 7

**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 | 1161 | 123.9 | 11.78 | 16.65 | 240.81 | 0.455 |
| 2.5 | 669 | 71.4 | 9.28 | 7.56 | 161.99 | 0.492 |
| 3.0 | 335 | 35.8 | 8.13 | 3.32 | 136.02 | 0.637 |
| 3.5 | 115 | 12.3 | 7.17 | 1.00 | 142.90 | 0.960 |
| 4.0 | 66 | 7.1 | 8.14 | 0.65 | 157.99 | 1.547 |
| 4.5 | 40 | 4.3 | 6.82 | 0.33 | 94.38 | 1.536 |
| 5.0 | 19 | 2.0 | 6.55 | 0.15 | 45.05 | 1.540 |
| 5.5 | 10 | 1.1 | 4.50 | 0.09 | 20.00 | 1.414 |
| 6.0 | 4 | 0.4 | 1.50 | 0(0) | 0.00 | 0.0 |

Note: Mean number of events per year calculated based on total number of valid records equivalent to 9.37 years of data.

## TABLE 8

**Monthly Mean $H_S$**

| Year | Month 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | - | - | - | - | 1.10* | 0.80 | 1.03 | 0.89 | 1.09 | 1.50 | 1.58 | 1.89 |
| 1971 | 1.14 | 1.24 | 1.37 | 1.20 | - | - | - | - | - | - | - | - |
| 1975 | - | - | - | - | - | - | - | - | - | - | 1.51 | 1.43 |
| 1976 | 1.84 | 1.29 | 1.52 | 1.14 | 0.92 | 0.62 | 0.74 | 0.81 | 1.33 | 1.35 | 1.29 | 1.64 |
| 1977 | 1.51 | 1.33 | (1.09) | - | - | - | (1.16) | 1.32 | 1.43 | 1.27 | 2.19 | 1.68 |
| 1978 | 1.74 | 1.60 | 1.41 | 1.49 | 1.04 | 1.04 | 1.08 | 1.11 | 1.47 | 1.18 | 1.65 | 2.23 |
| 1979 | 1.98 | 2.22 | 1.92 | 1.24* | 1.08 | 0.80 | 0.81 | 1.02 | 1.17 | 1.48 | 1.57 | 1.94 |
| 1980 | 1.62 | 1.22 | 1.54 | 1.23 | 1.28 | 0.95 | 1.21 | 1.10 | 1.06 | 1.86 | 2.19 | 2.00 |
| 1981 | 1.81 | 1.63 | 1.44 | 1.62 | 1.13 | (1.11) | - | - | - | - | - | - |
| 1982 | (1.13) | 1.19 | (1.14) | 1.02 | 0.85 | 0.85 | 0.76 | 0.85 | 0.85 | 1.22 | 1.43 | 1.48 |
| 1983 | - | - | - | (1.30) | 0.85 | 0.83 | 0.50 | 0.76 | 1.27 | 1.52 | 1.25 | 1.55 |
| 1984 | 2.06 | 1.46 | 1.36 | 0.79 | 1.20 | 1.04 | 0.89 | 0.60 | 1.40 | 1.32 | 1.58 | 1.29 |
| 1985 | 1.82 | (1.11) | - | - | - | (0.57) | 0.72 | 1.00 | 0.93 | 1.01 | 1.95 | 1.43 |

## TABLE 9

**Monthly Maximum $H_S$**

| Year | Month 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | - | - | - | - | 2.51* | 1.78 | 3.94 | 3.58 | 3.39 | 4.77 | 4.09 | 4.83 |
| 1971 | 2.48 | 4.53 | 3.53 | 3.54 | - | - | - | - | - | - | - | - |
| 1975 | - | - | - | - | - | - | - | - | - | - | 5.23 | 3.94 |
| 1976 | 4.13 | 4.45 | 2.98 | 2.75 | 2.52 | 1.77 | 2.45 | 3.09 | 3.67 | 2.97 | 3.76 | 4.03 |
| 1977 | 3.52 | 2.85 | (2.42) | - | - | - | (3.10) | 3.70 | 3.18 | 4.13 | 4.43 | 4.12 |
| 1978 | 5.69 | 3.71 | 3.33 | 3.65 | 2.98 | 2.47 | 2.83 | 3.11 | 3.09 | 3.91 | 4.91 | 5.61 |
| 1979 | 4.93 | 6.29 | 6.05 | 3.59* | 2.74 | 2.92 | 1.89 | 2.92 | 2.81 | 3.67 | 3.35 | 5.04 |
| 1980 | 5.01 | 3.89 | 4.75 | 4.70 | 3.61 | 2.82 | 3.60 | 3.16 | 2.68 | 5.33 | 5.53 | 4.67 |
| 1981 | 4.28 | 4.16 | 3.85 | 5.04 | 3.20 | (2.67) | - | - | - | - | - | - |
| 1982 | (4.12) | 2.38 | (3.28) | 3.25 | 3.04 | 2.95 | 2.05 | 2.70 | 2.94 | 3.71 | 3.20 | 4.58 |
| 1983 | - | - | - | (3.27) | 2.90 | 1.98 | 1.39 | 2.50 | 3.90 | 3.48 | 3.10 | 4.61 |
| 1984 | 4.93 | 3.57 | 5.27 | 2.63 | 3.05 | 2.90 | 2.91 | 2.14 | 3.68 | 3.90 | 3.21 | 3.30 |
| 1985 | 3.82 | (2.10) | - | - | - | (0.94) | 2.37 | 3.78 | 2.74 | 2.52 | 3.60 | 4.32 |

## TABLE 10
### Monthly Median $H_S$

| Year | Month 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | - | - | - | - | 0.99* | 0.75 | 0.83 | 0.78 | 1.04 | 1.31 | 1.45 | 1.75 |
| 1971 | 1.04 | 1.06 | 1.23 | 1.07 | - | - | - | - | - | - | - | - |
| 1975 | - | - | - | - | - | - | - | - | - | - | 1.34 | 1.23 |
| 1976 | 1.64 | 1.12 | 1.44 | 1.11 | 0.91 | 0.51 | 0.69 | 0.68 | 1.19 | 1.32 | 1.10 | 1.64 |
| 1977 | 1.43 | 1.25 | (1.05) | - | - | - | (1.14) | 1.28 | 1.38 | 1.12 | 2.12 | 1.54 |
| 1978 | 1.50 | 1.55 | 1.31 | 1.34 | 0.99 | 0.99 | 0.99 | 1.06 | 1.41 | 1.09 | 1.47 | 1.98 |
| 1979 | 1.70 | 1.85 | 1.65 | 1.13* | 1.00 | 0.68 | 0.75 | 0.87 | 1.03 | 1.37 | 1.46 | 1.89 |
| 1980 | 1.50 | 1.56 | 1.38 | 1.04 | 1.29 | 0.84 | 0.98 | 0.97 | 1.01 | 1.74 | 2.04 | 1.83 |
| 1981 | 1.75 | 1.48 | 1.31 | 1.42 | 1.00 | (1.13) | - | - | - | - | - | - |
| 1982 | (0.95) | 1.19 | (1.16) | 0.65 | 0.67 | 0.69 | 0.65 | 0.70 | 0.61 | 1.13 | 1.34 | 1.40 |
| 1983 | - | - | - | (1.12) | 0.74 | 0.84 | 0.25 | 0.73 | 1.22 | 1.53 | 1.20 | 1.43 |
| 1984 | 2.00 | 1.44 | 1.25 | 0.73 | 1.13 | 0.88 | 0.85 | 0.50 | 1.23 | 1.21 | 1.49 | 1.23 |
| 1985 | 1.75 | (1.28) | - | - | - | (0.58) | 0.67 | 0.89 | 0.79 | 0.95 | 1.83 | 1.30 |

## TABLE 11
### Monthly 90th Percentile $H_S$

| Year | Month 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | - | - | - | - | 1.91* | 1.31 | 2.18 | 1.49 | 1.91 | 2.92 | 2.56 | 3.09 |
| 1971 | 1.93 | 2.00 | 2.21 | 1.97 | - | - | - | - | - | - | - | - |
| 1975 | - | - | - | - | - | - | - | - | - | - | 2.39 | 2.37 |
| 1976 | 3.10 | 2.37 | 2.28 | 1.86 | 1.39 | 1.19 | 1.22 | 1.57 | 2.25 | 2.14 | 2.24 | 2.55 |
| 1977 | 2.42 | 2.05 | (1.56) | - | - | - | (1.60) | 2.27 | 2.19 | 2.22 | 3.23 | 3.05 |
| 1978 | 2.79 | 2.55 | 2.25 | 2.33 | 1.91 | 1.89 | 1.82 | 1.86 | 2.13 | 2.04 | 2.81 | 3.64 |
| 1979 | 3.45 | 4.57 | 3.10 | 2.11* | 1.86 | 1.37 | 1.38 | 1.88 | 1.98 | 2.52 | 2.52 | 3.03 |
| 1980 | 2.52 | 1.85 | 2.37 | 2.20 | 2.04 | 1.73 | 2.28 | 2.01 | 1.75 | 2.76 | 3.35 | 3.09 |
| 1981 | 3.17 | 2.82 | 2.29 | 3.46 | 2.05 | (1.74) | - | - | - | - | - | - |
| 1982 | (2.15) | 2.05 | (2.15) | 2.34 | 1.96 | 1.89 | 1.40 | 1.79 | 1.99 | 2.55 | 2.47 | 2.58 |
| 1983 | - | - | - | (2.43) | 1.67 | 1.36 | 1.01 | 1.34 | 2.32 | 2.37 | 2.28 | 2.47 |
| 1984 | 3.21 | 2.56 | 2.15 | 1.46 | 2.11 | 2.07 | 1.62 | 1.16 | 2.42 | 2.47 | 2.47 | 2.22 |
| 1985 | 2.84 | (1.73) | - | - | - | (0.84) | 1.13 | 1.83 | 1.77 | 1.68 | 3.09 | 2.20 |

DOWSING LV SBWR 1970-85

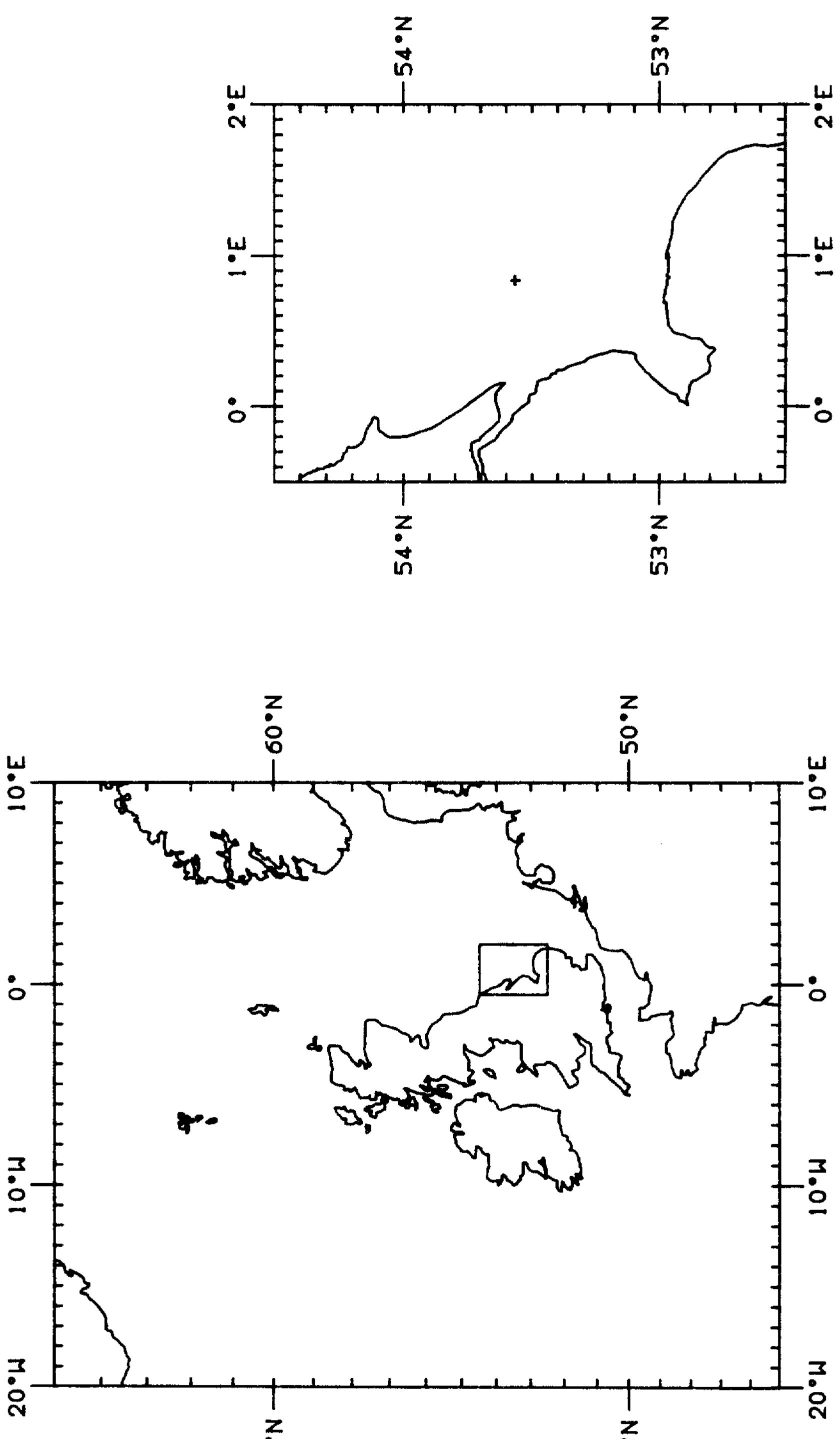



Figure 1

DOWSING LV SBWR 1970-85
Percentage Occurrence Histograms for Hs and Tz
ALL DATA

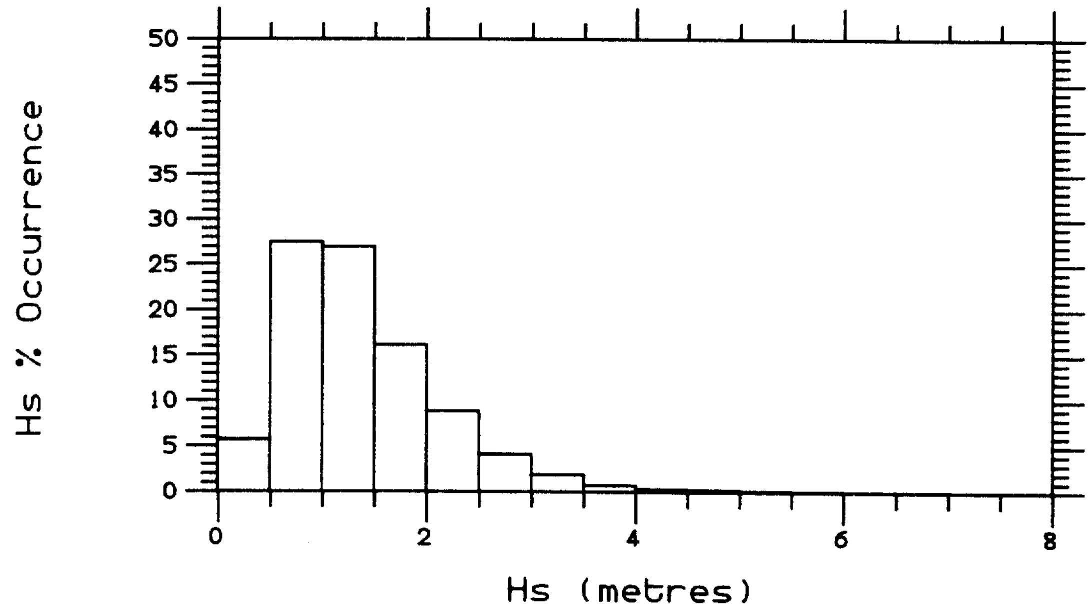



Figure 2a

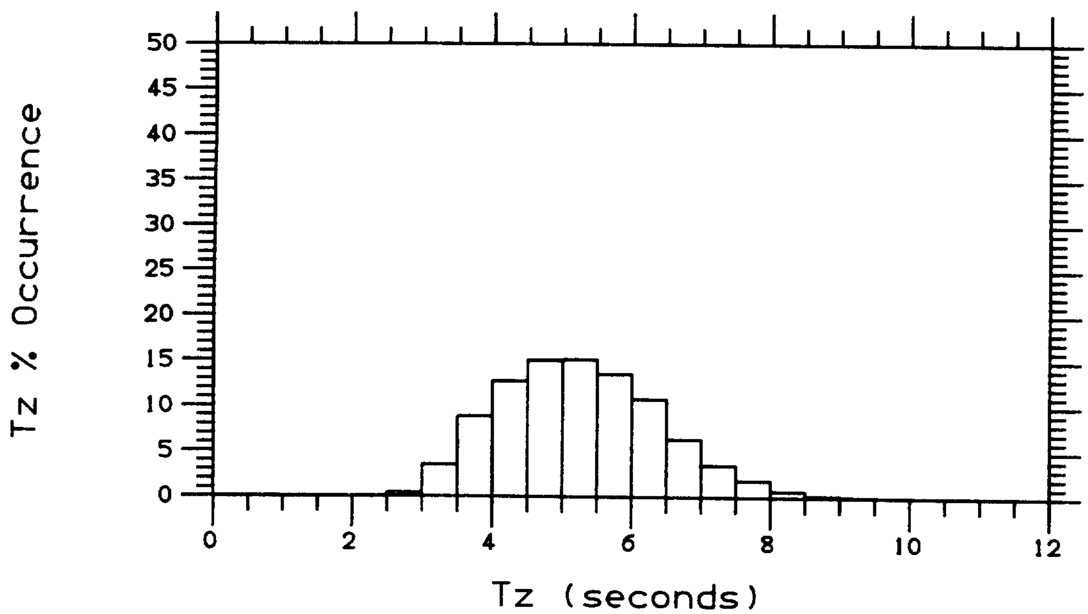



Figure 2b

DOWSING LV SBWR 1970-85
Percentage Occurrence Histograms for Hs and Tz
SPRING

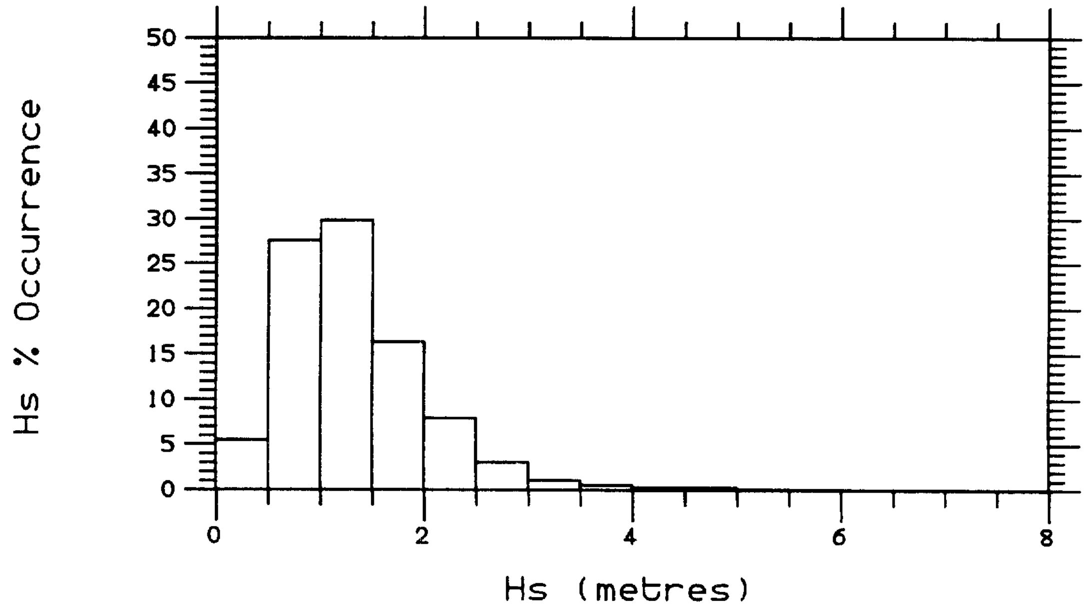



Figure 2c

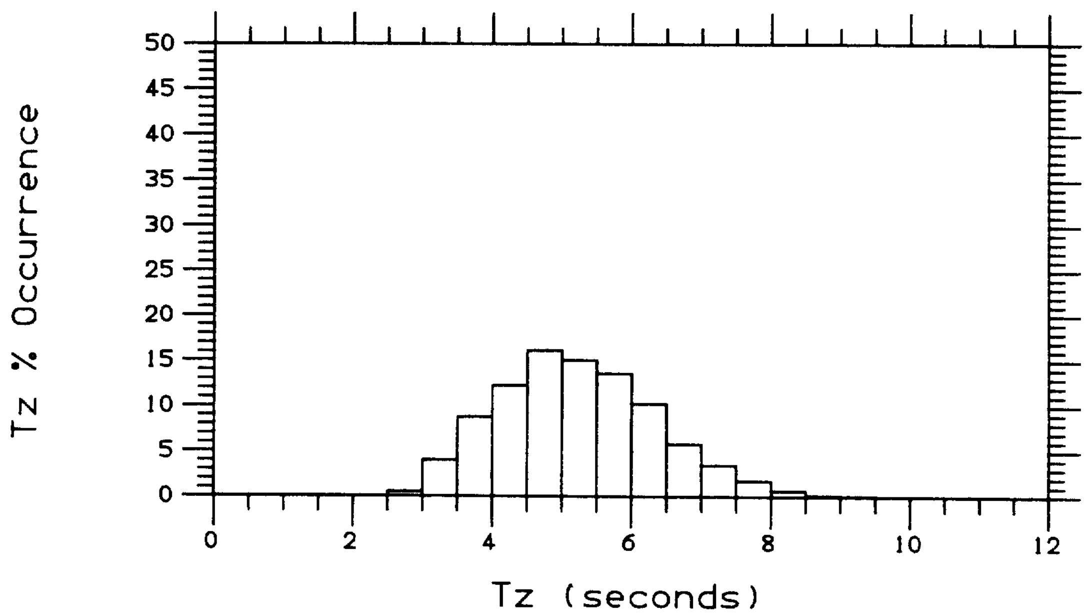



Figure 2d

DOWSING LV SBWR 1970-85
Percentage Occurrence Histograms for Hs and Tz
SUMMER

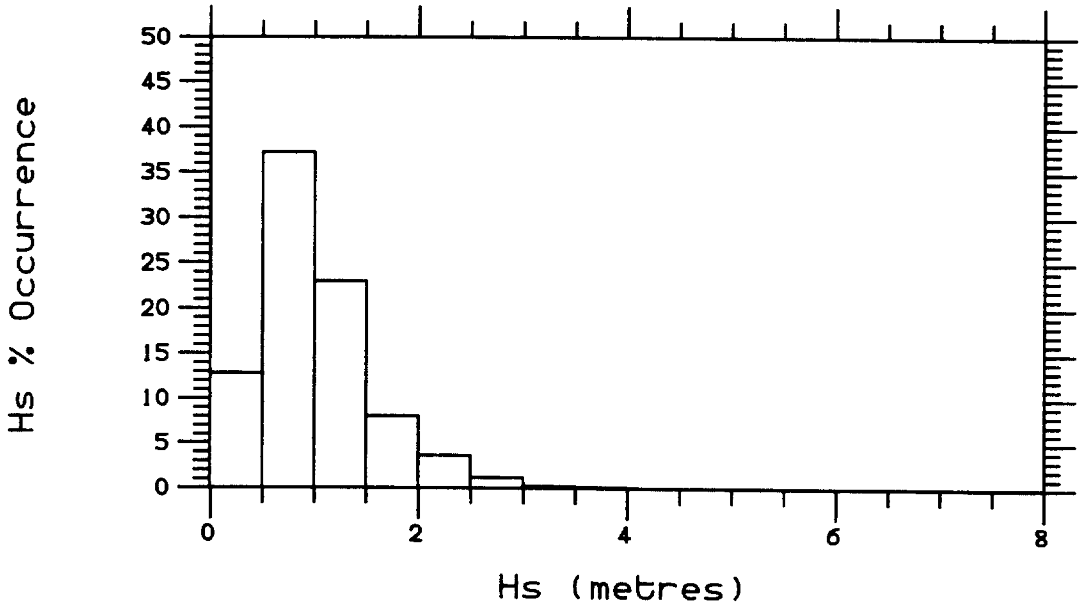



Figure 2e

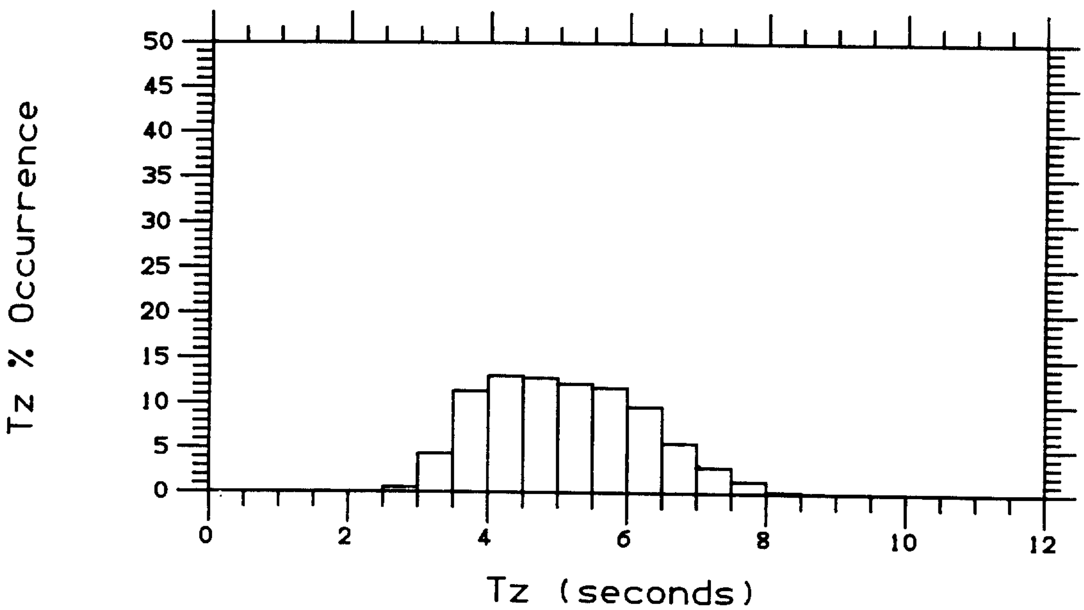



Figure 2f

DOWSING LV SBWR 1970-85
Percentage Occurrence Histograms for Hs and Tz
AUTUMN

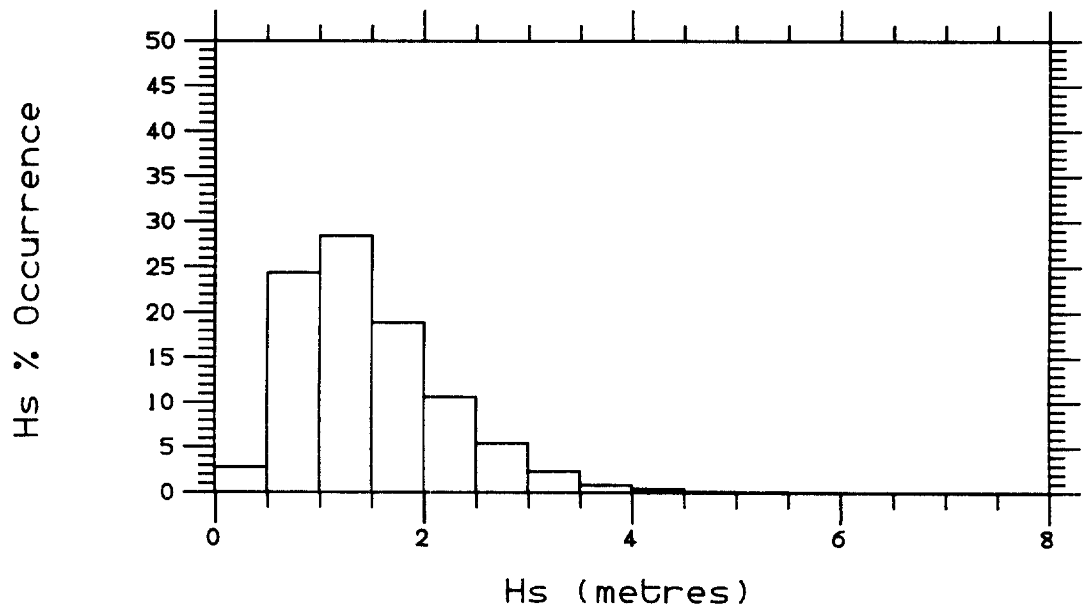



Figure 2g

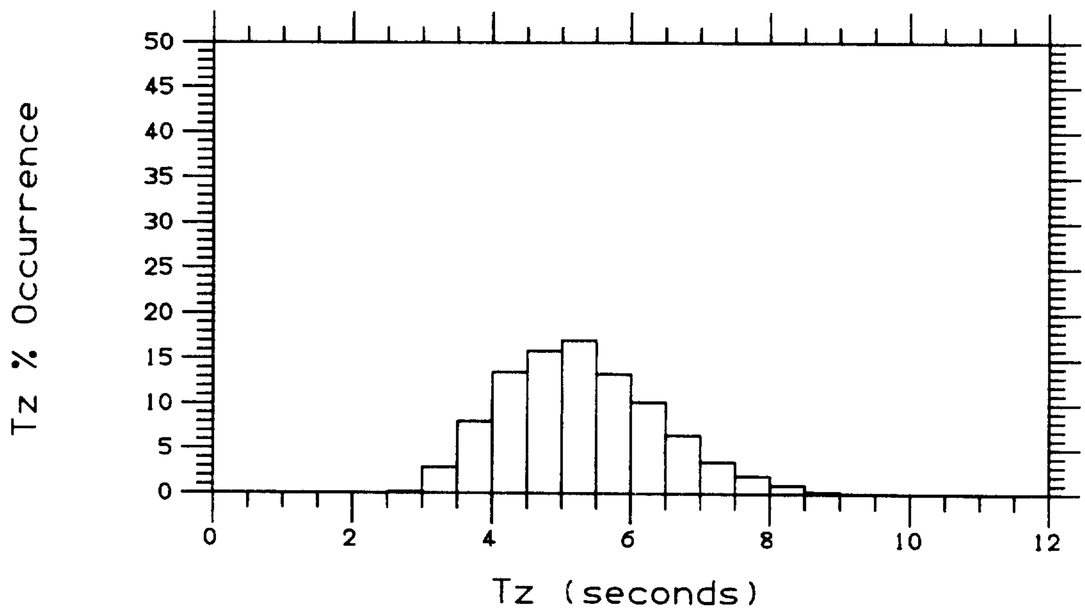



Figure 2h

DOWSING LV SBWR 1970-85
Percentage Occurrence Histograms for Hs and Tz
WINTER

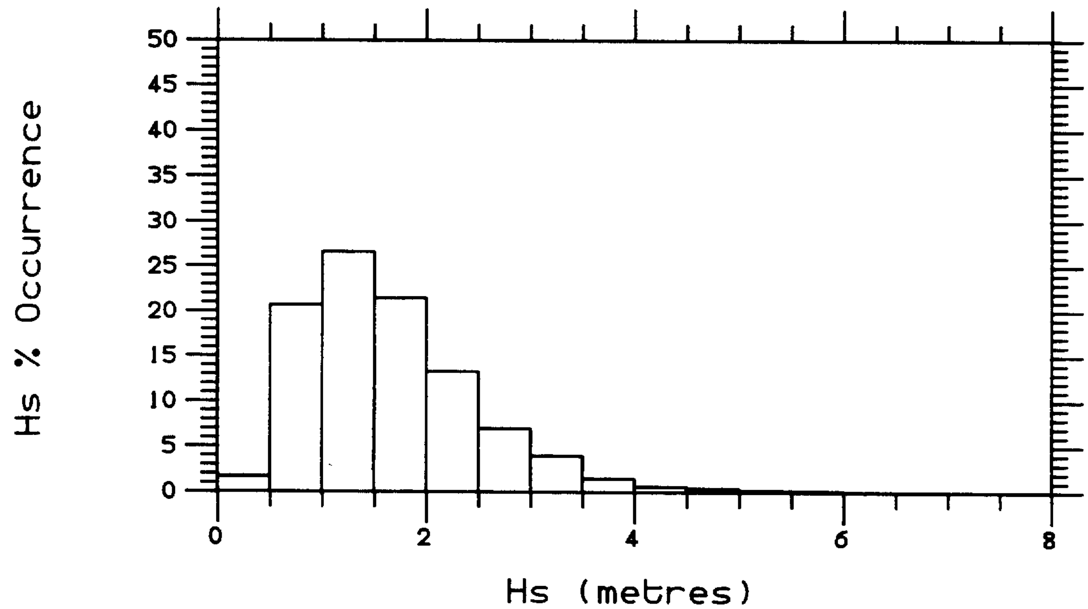



Figure 2i

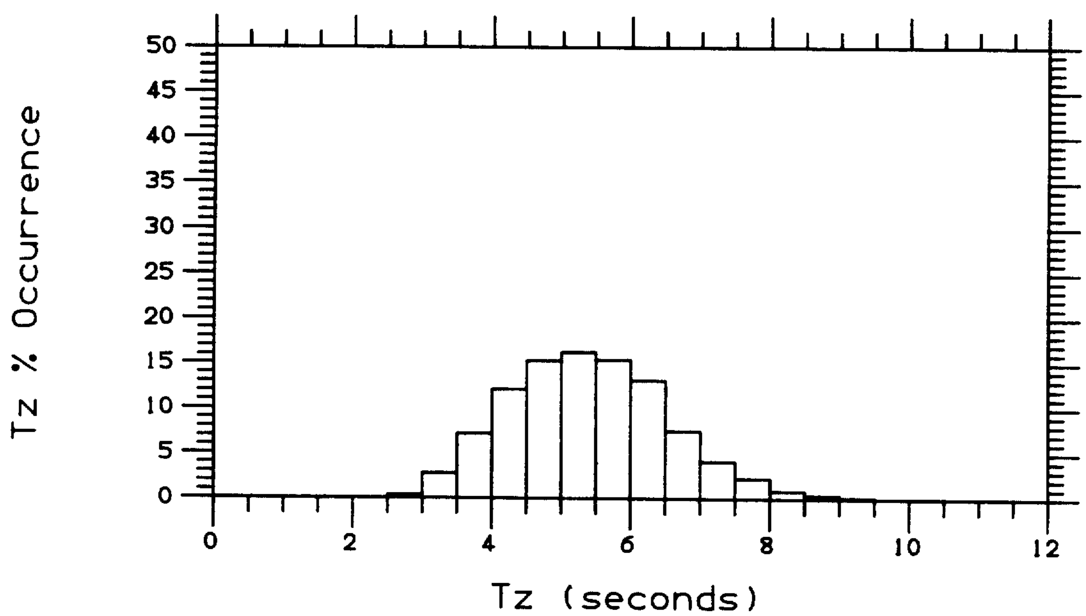



Figure 2j

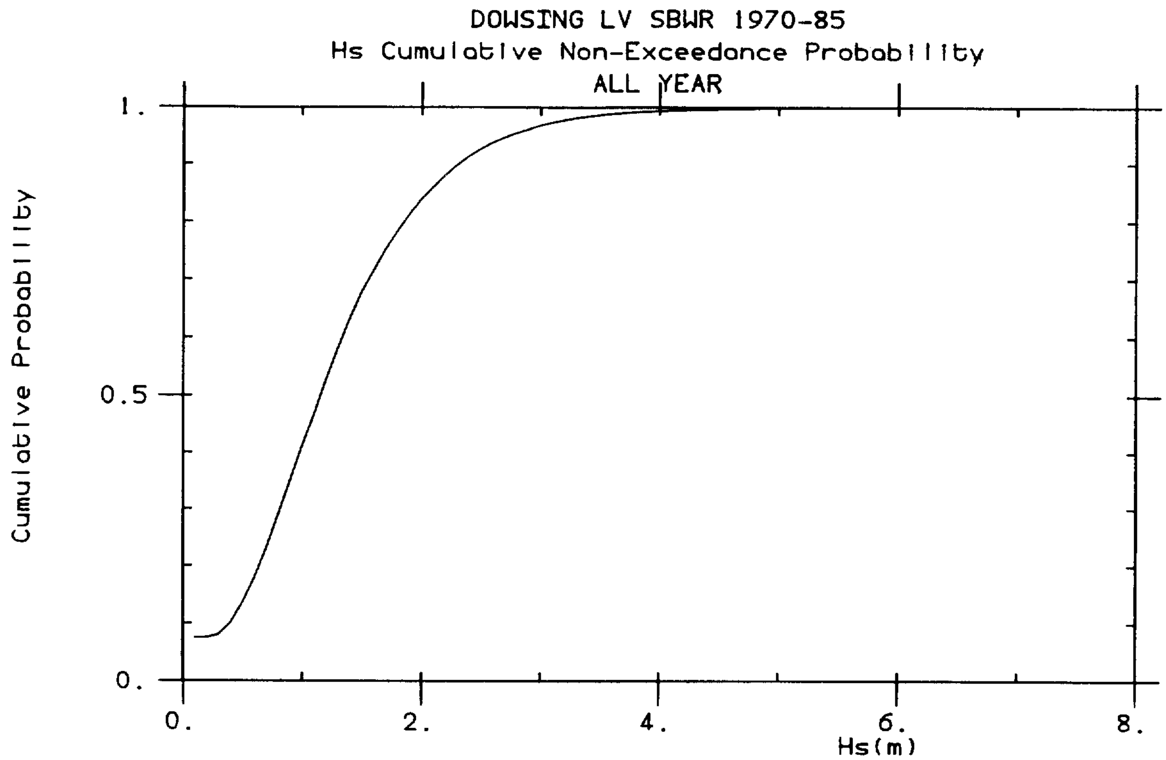



Figure 3a

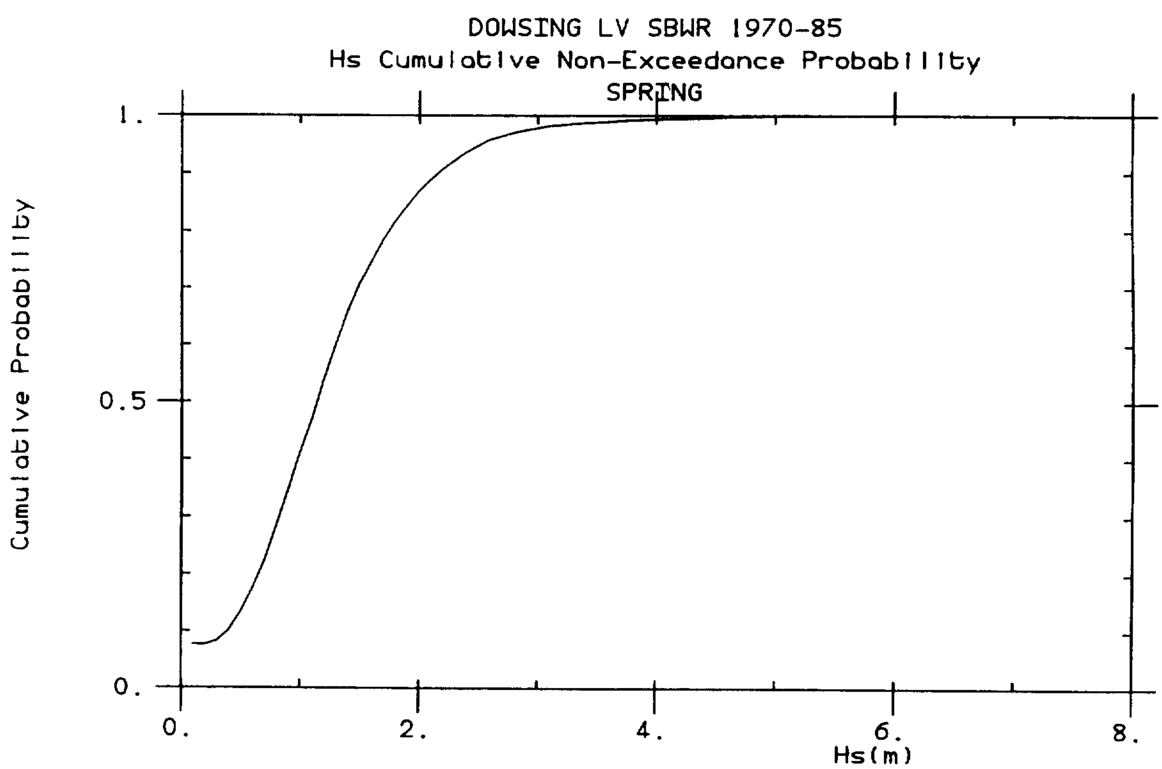



Figure 3b

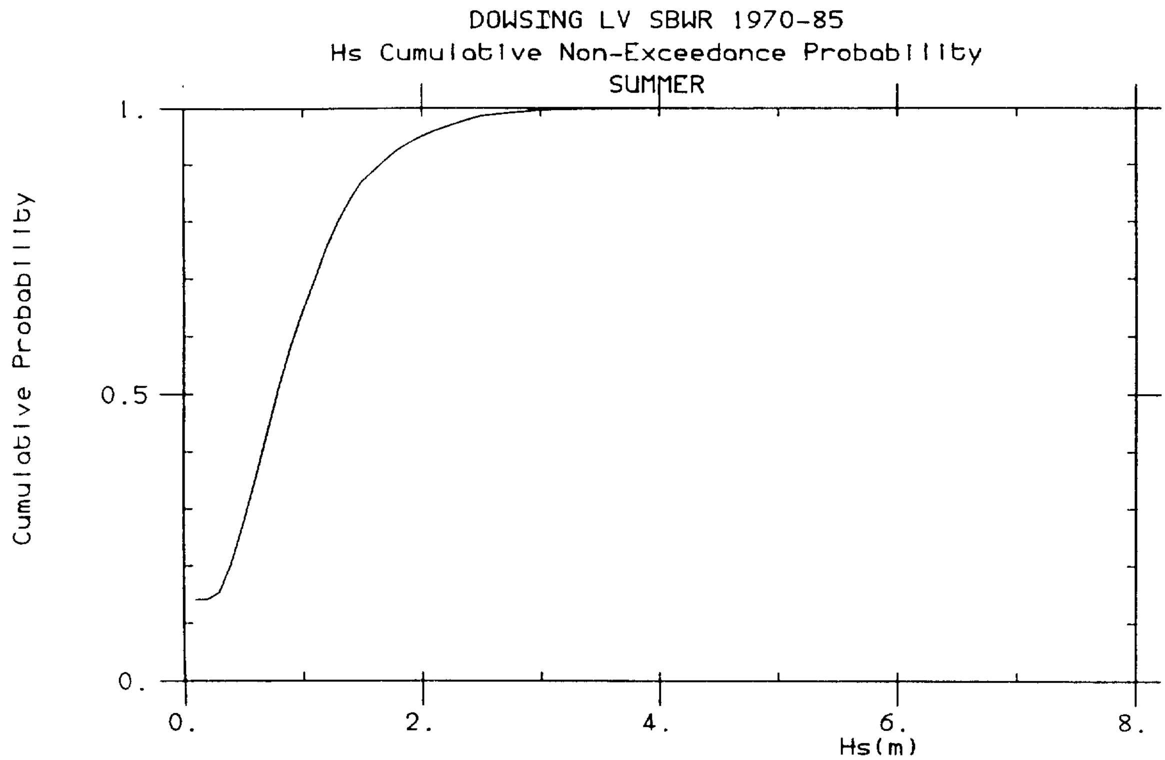



Figure 3c

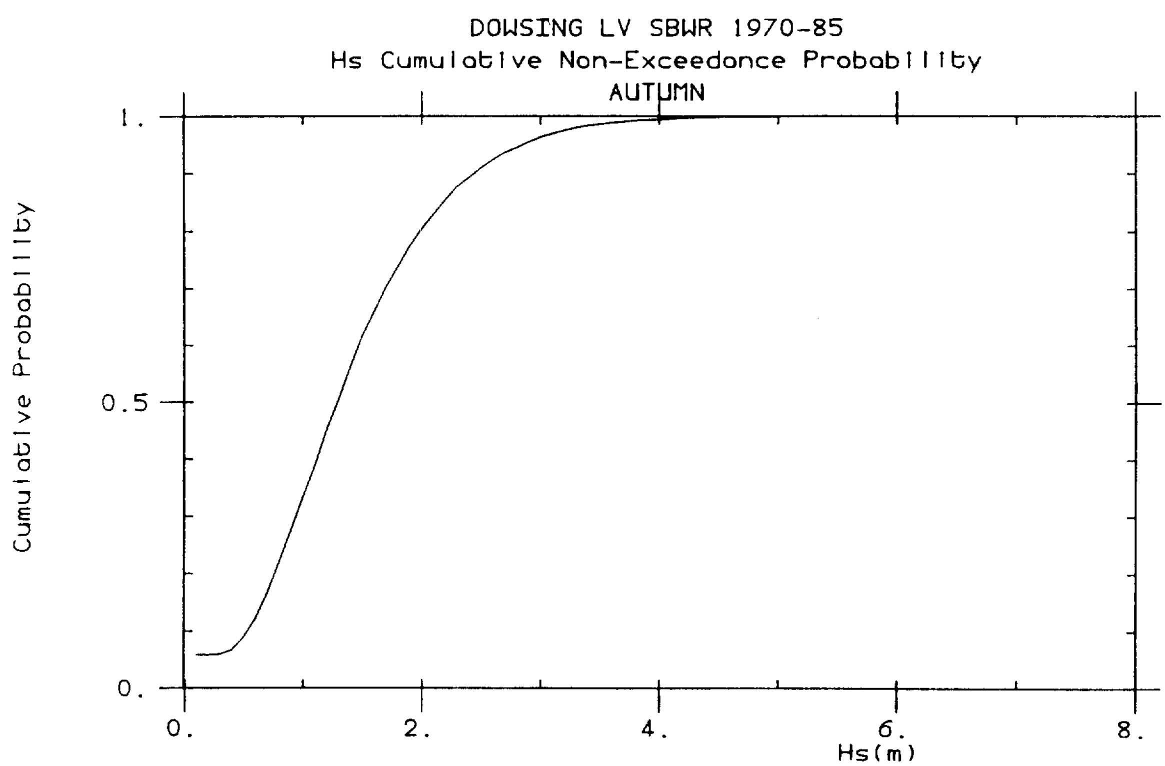



Figure 3d

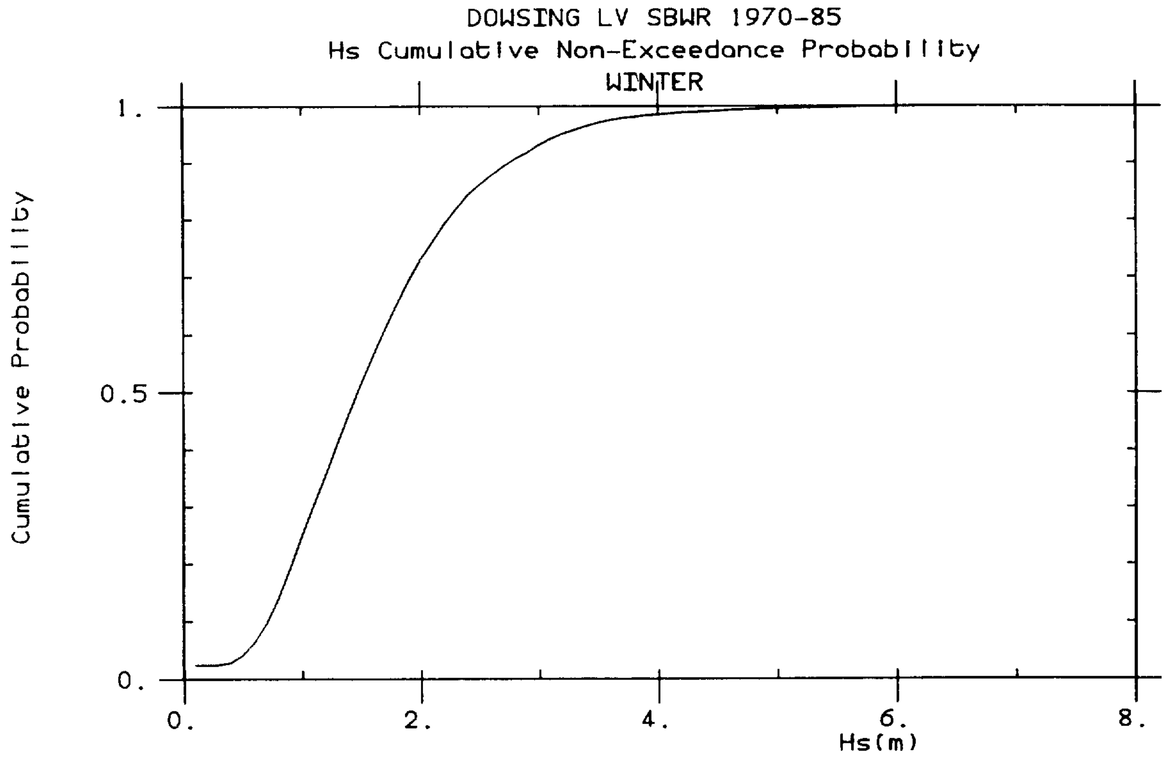
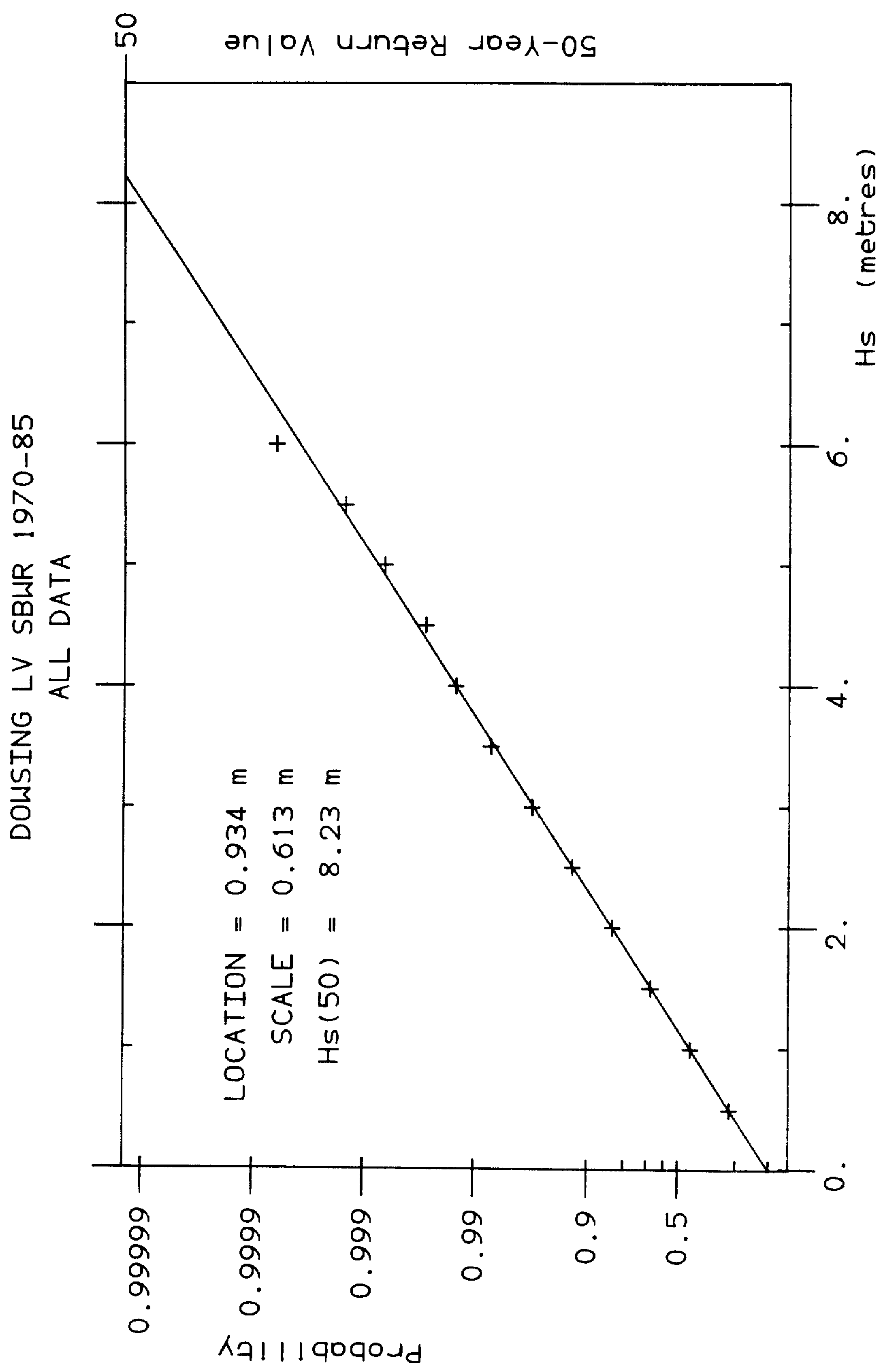

DOWSING LV SBWR 1970-85
Hs Cumulative Non-Exceedance Probability
WINTER
Cumulative Probability
1.
0.5
0.
0.
2.
4.
6.
8.
Hs(m)

Figure 3e




CUMULATIVE HS PROBABILITY on FT-1 SCALE

Figure 4

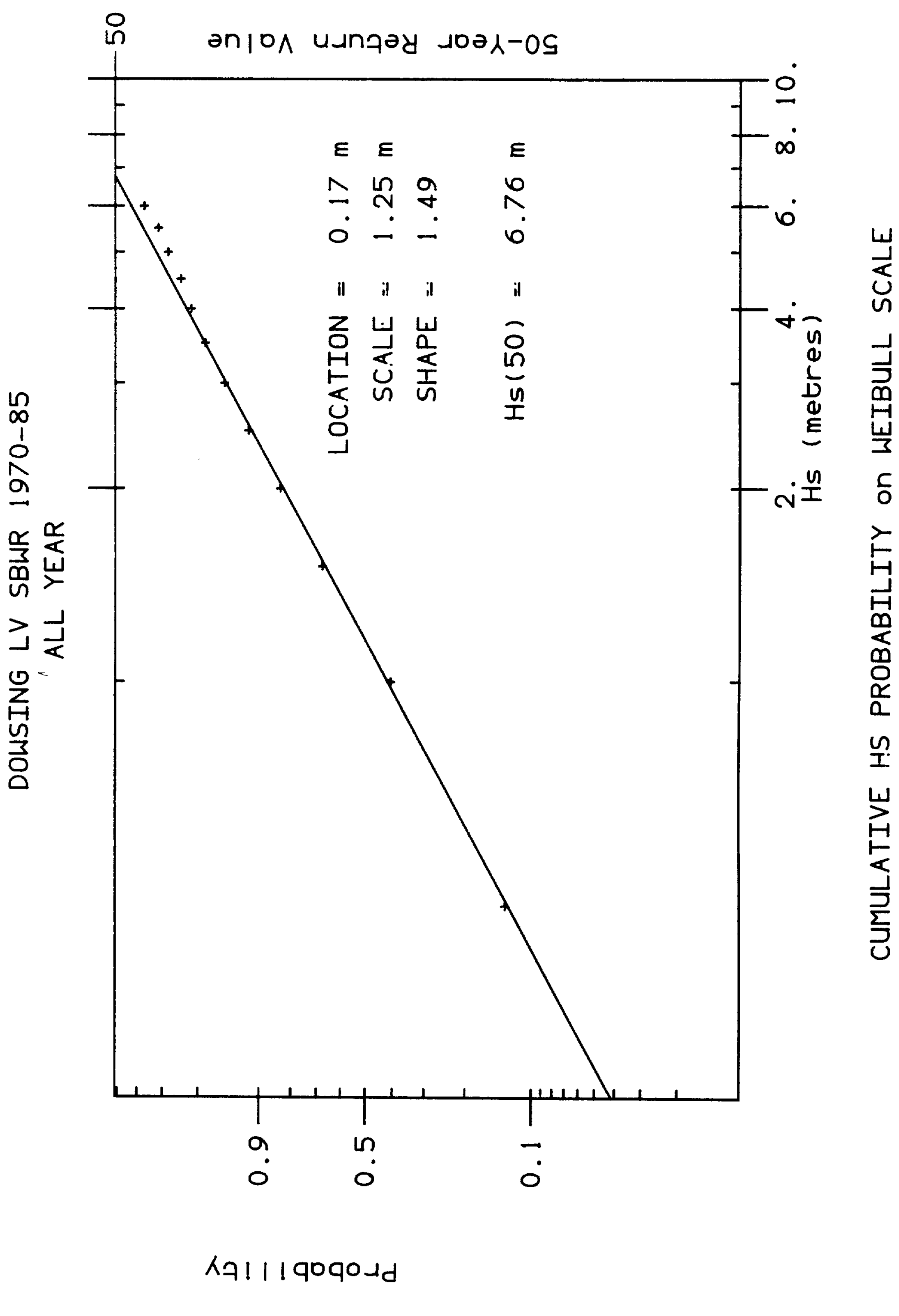

DOWSING LV SBWR 1970-85
ALL YEAR
50-Year Return Value
50
LOCATION = 0.17 m
SCALE = 1.25 m
SHAPE = 1.49
Hs(50) = 6.76 m
2.
4.
6.
8.
10.
Hs (metres)
0.9
0.5
0.1
Probability
CUMULATIVE HS PROBABILITY on WEIBULL SCALE

Figure 5

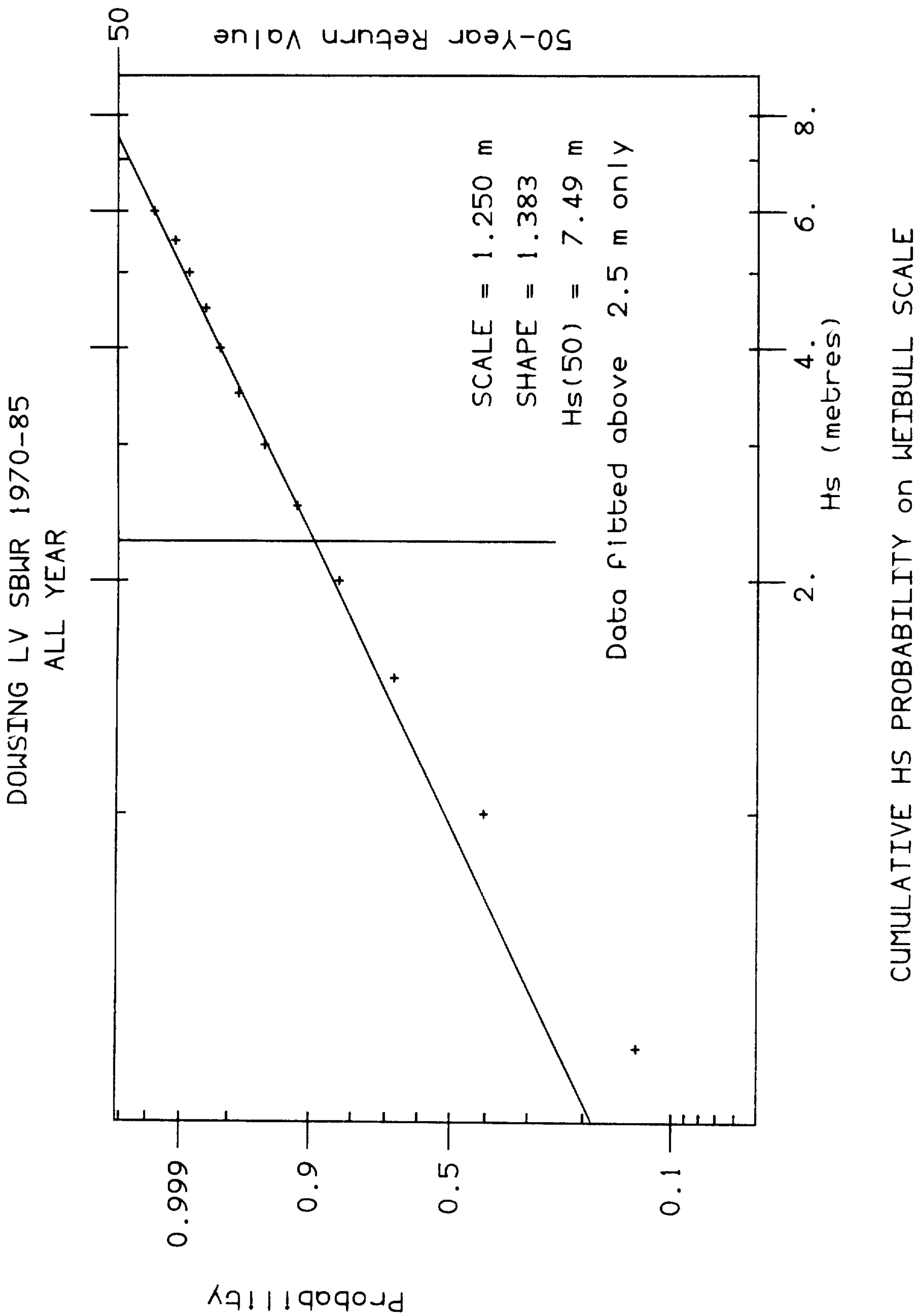

DOWSING LV SBWR 1970-85
ALL YEAR
50
50-Year Return Value
SCALE = 1.250 m
SHAPE = 1.383
Hs(50) = 7.49 m
Data fitted above 2.5 m only
0.999
0.9
0.5
0.1
Probability
2.
4.
6.
8.
Hs (metres)
CUMULATIVE HS PROBABILITY on WEIBULL SCALE

Figure 6

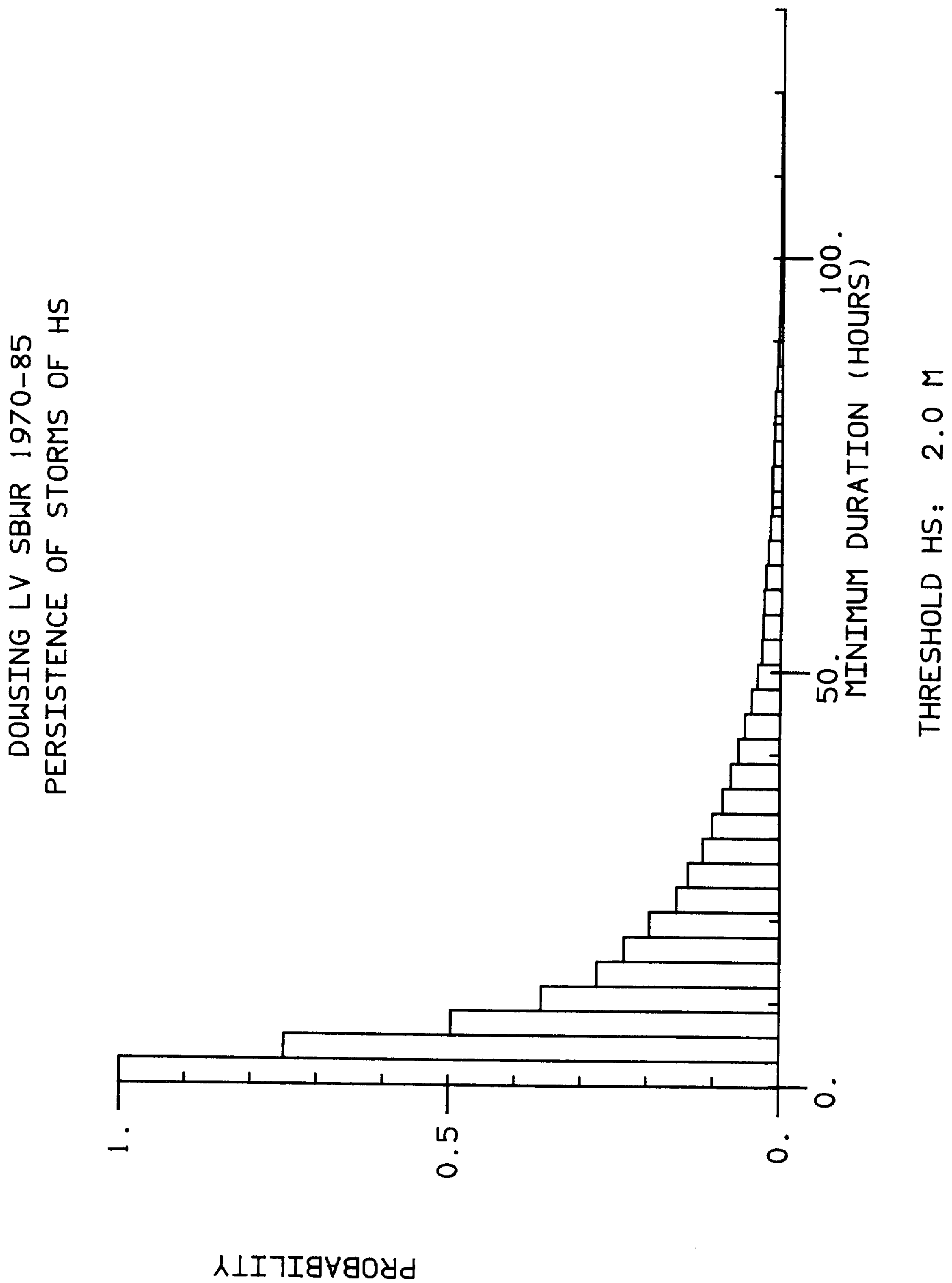

DOWSING LV SBWR 1970-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 2.0 M

Figure 7a

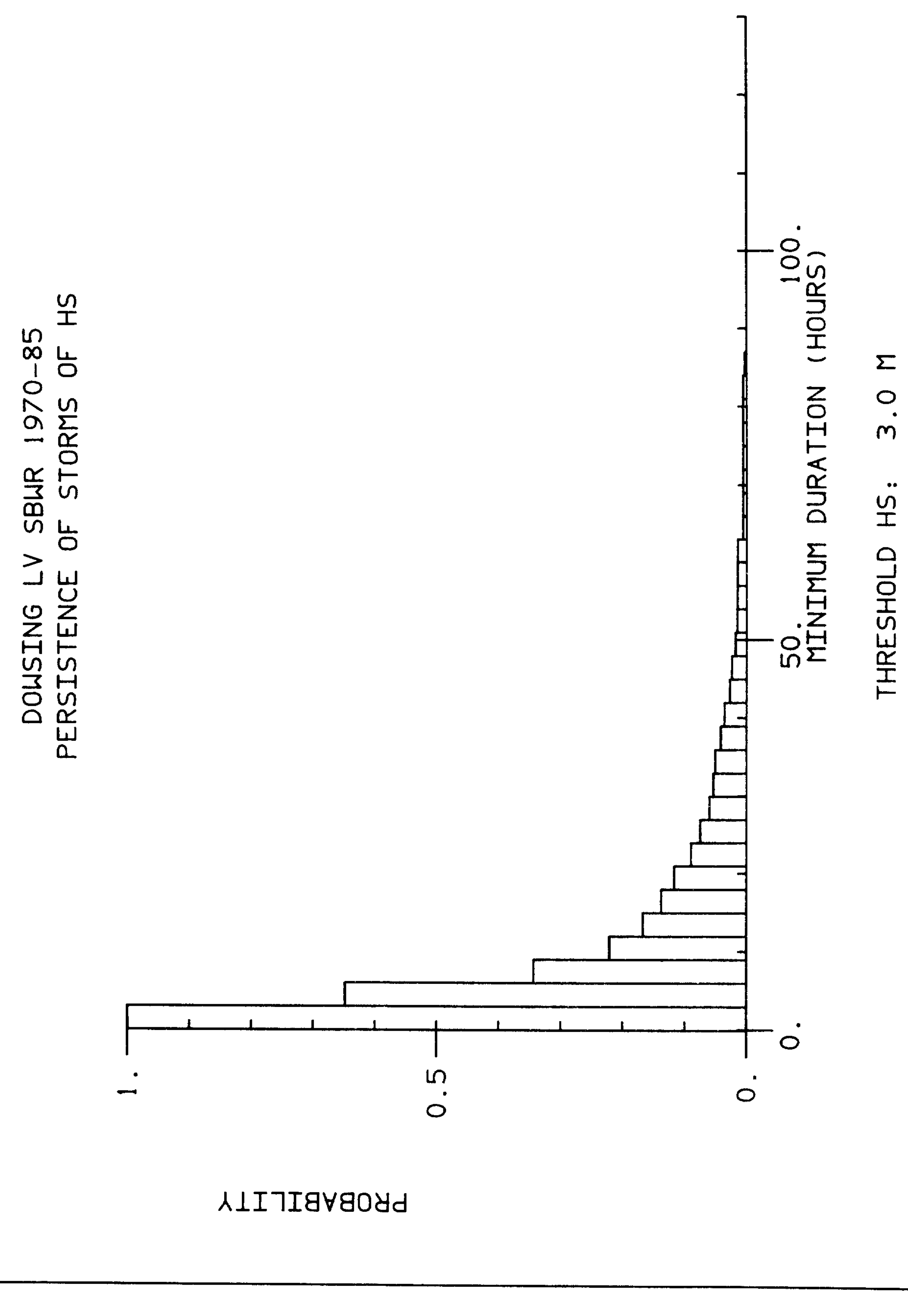

DOWSING LV SBWR 1970-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 3.0 M

Figure 7b

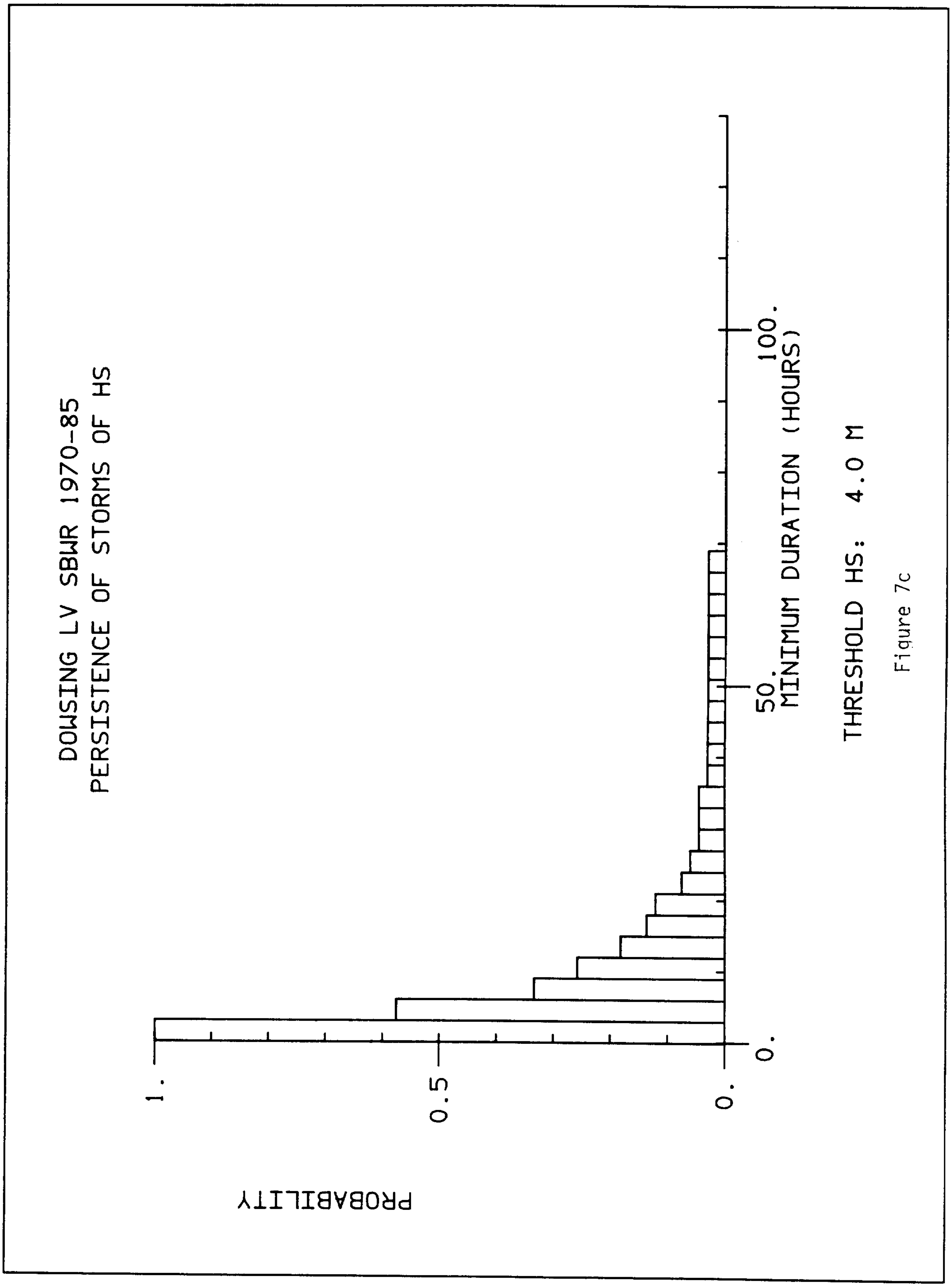

DOWSING LV SBWR 1970-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 4.0 M

Figure 7c

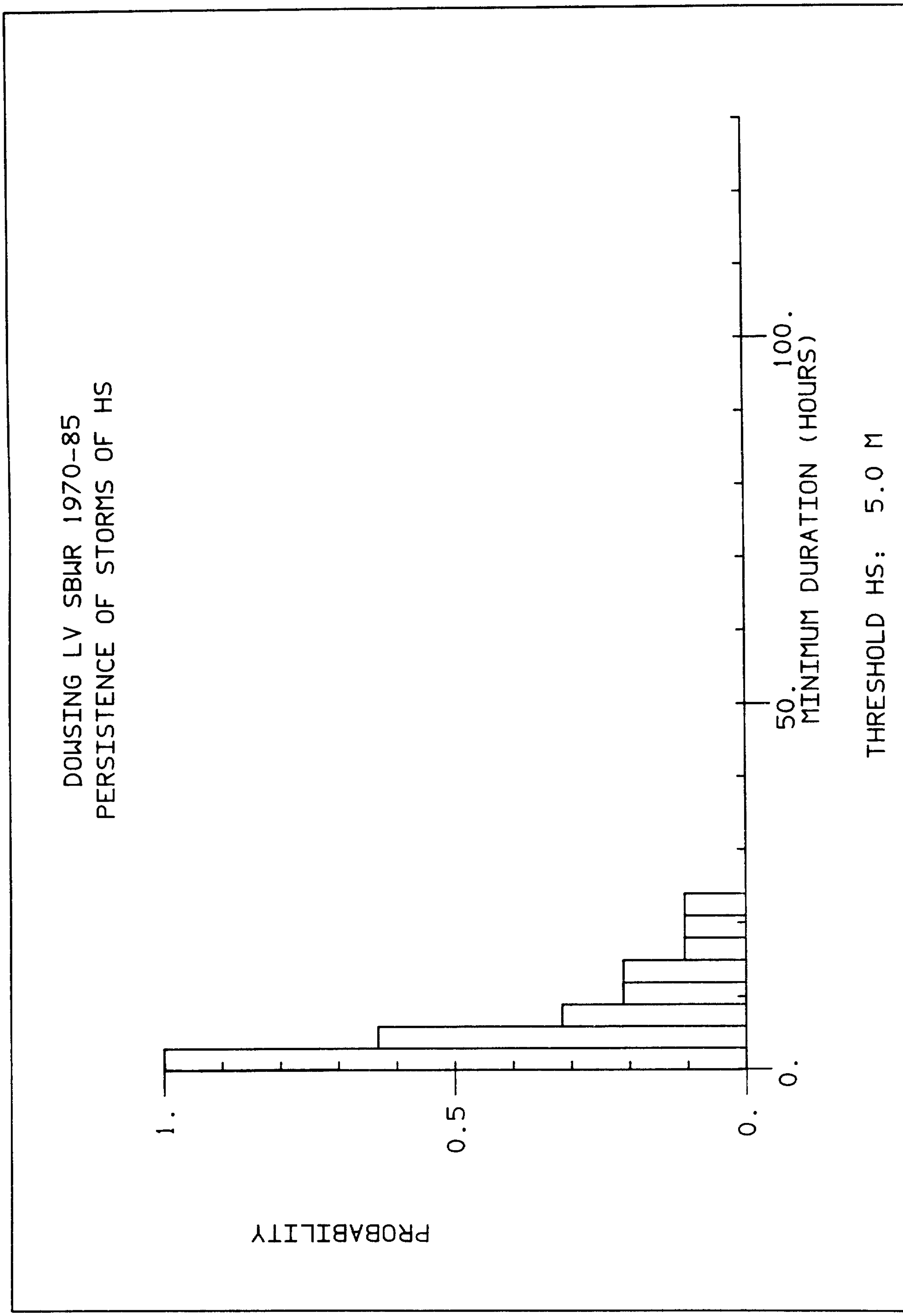
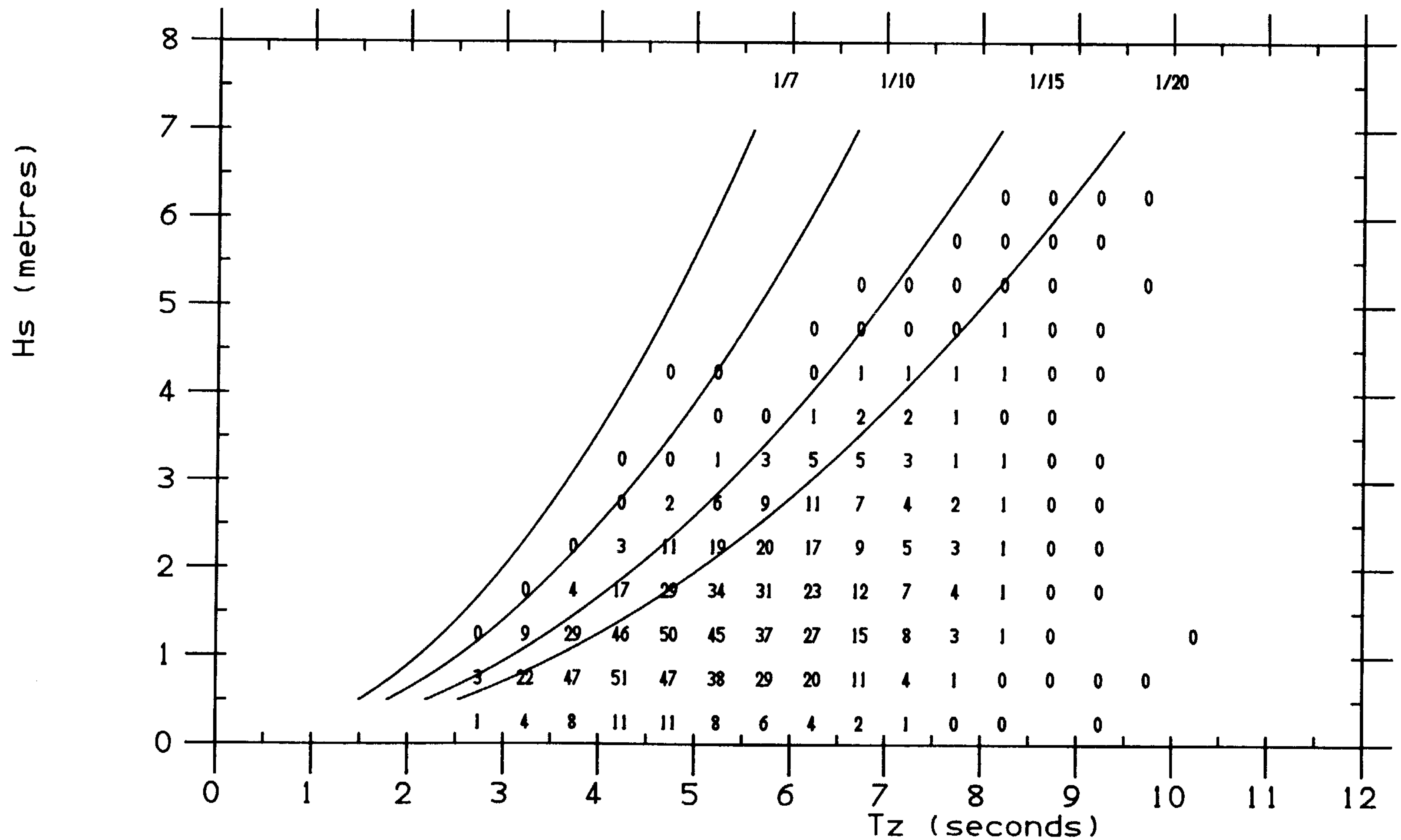

DOWSING LV SBWR 1970-85
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0.
50.
100.
MINIMUM DURATION (HOURS)
THRESHOLD HS: 5.0 M

Figure 7d

DOWSING LV SBWR 1970-85
HS,TZ SCATTERPLOT in parts per thousand
ALL DATA




CALMS = 7.6%

Figure 8a

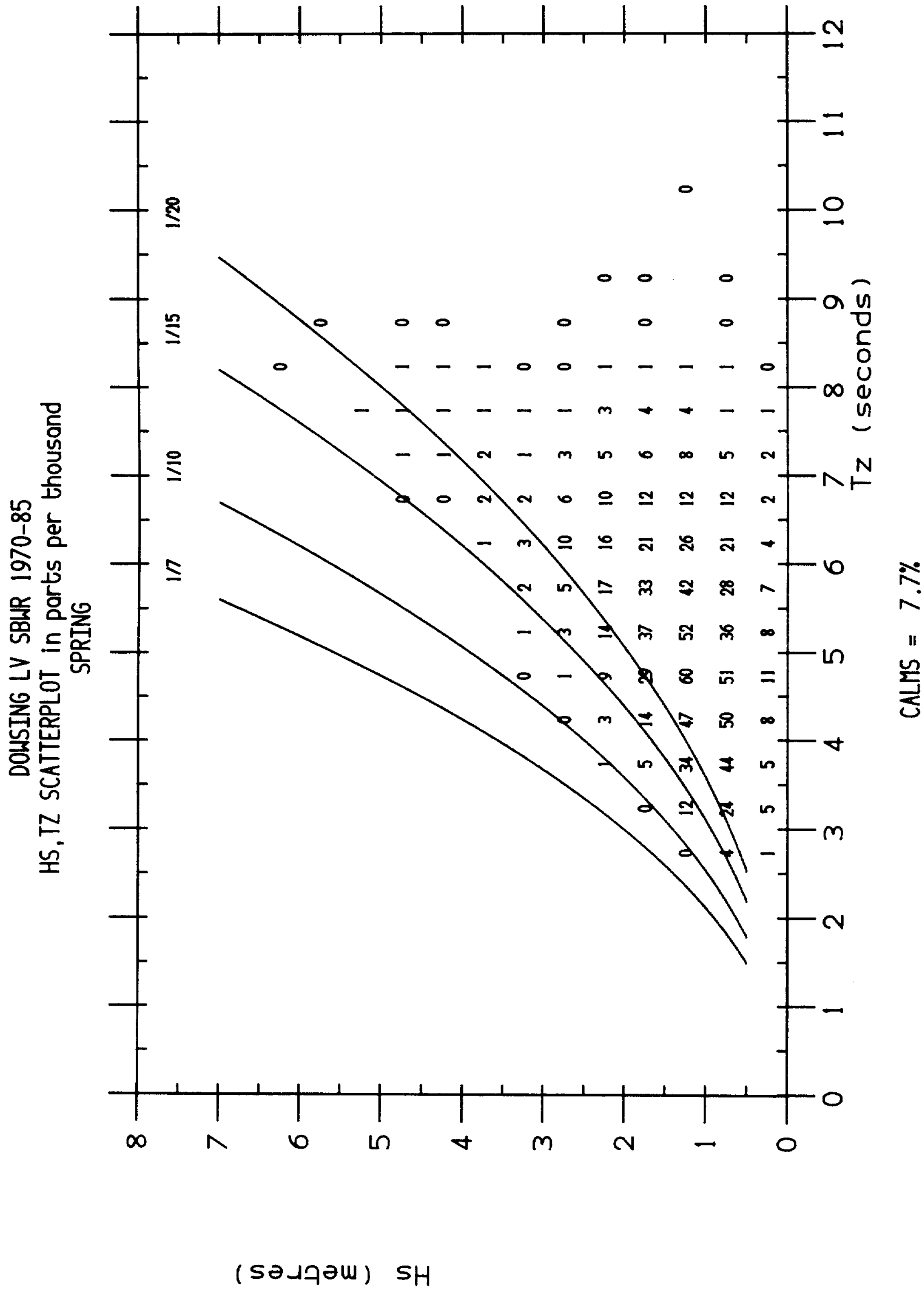

DOWSING LV SBWR 1970-85
HS,TZ SCATTERPLOT in parts per thousand
SPRING
1/7
1/10
1/15
1/20
Hs (metres)
Tz (seconds)
CALMS = 7.7%

Figure 8b

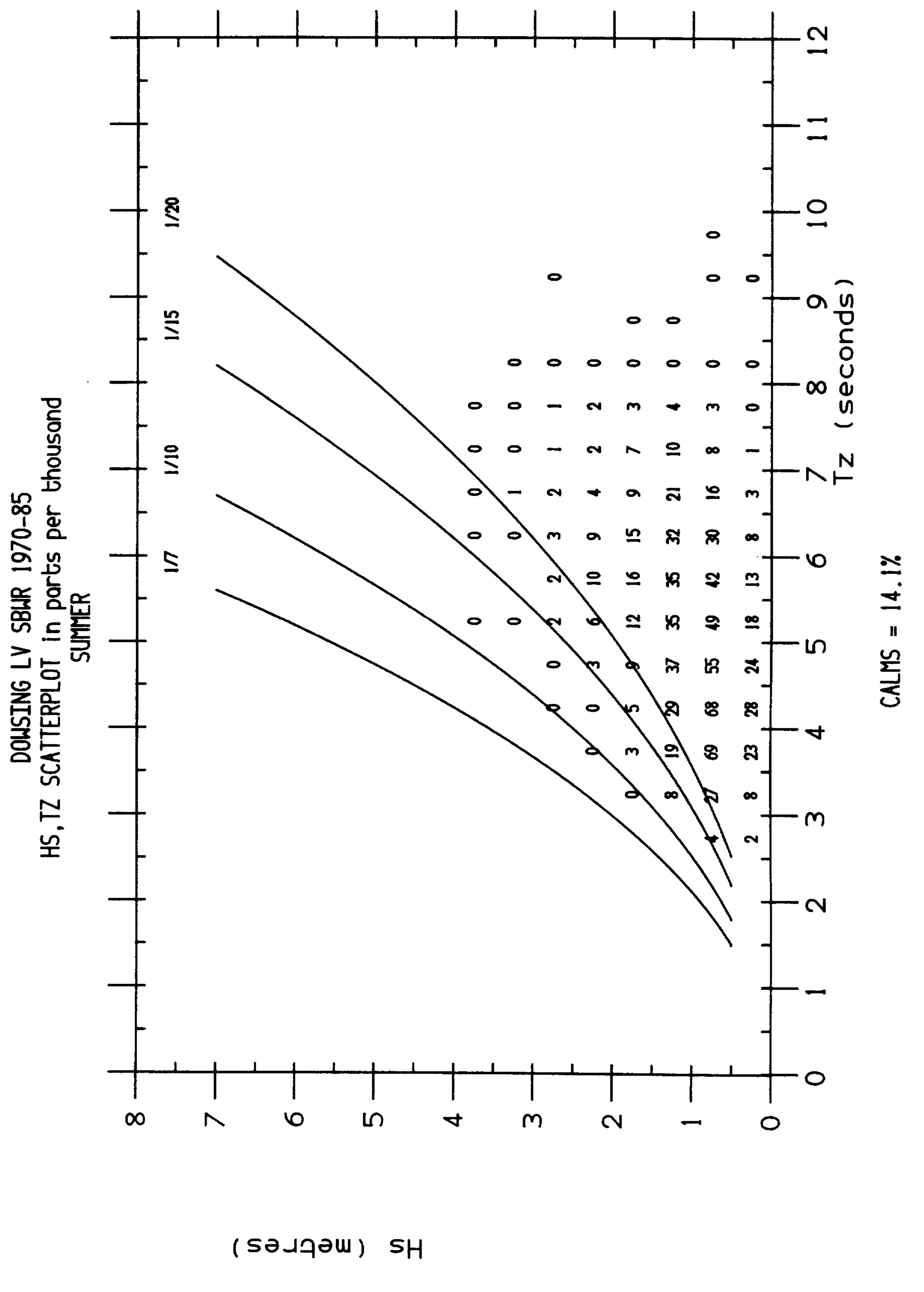
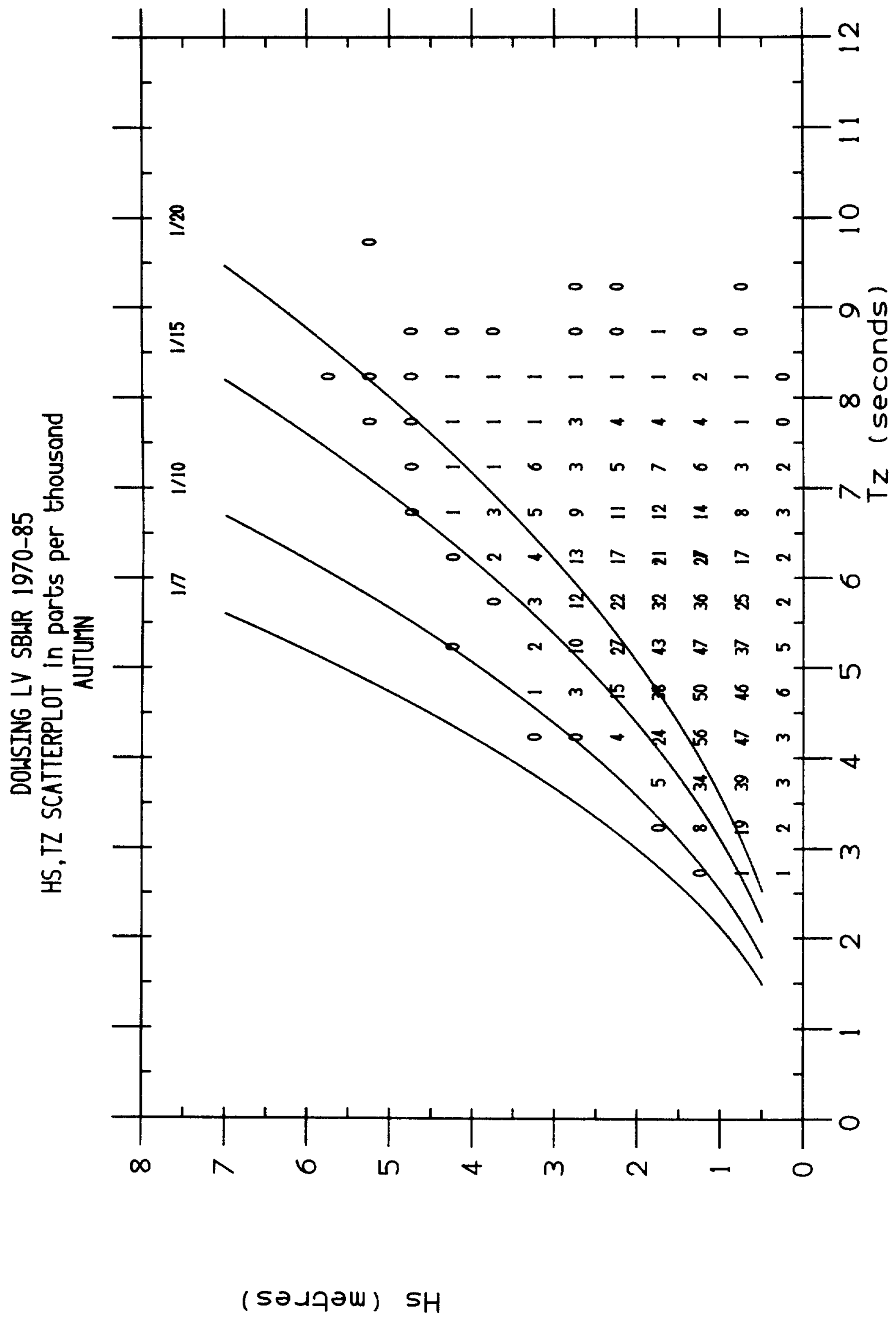

DOWSING LV SBWR 1970-85
HS,TZ SCATTERPLOT in parts per thousand
SUMMER
1/7
1/10
1/15
1/20
Hs (metres)
Tz (seconds)
CALMS = 14.1%

Figure 8c




CALMS = 5.9%

Figure 8d

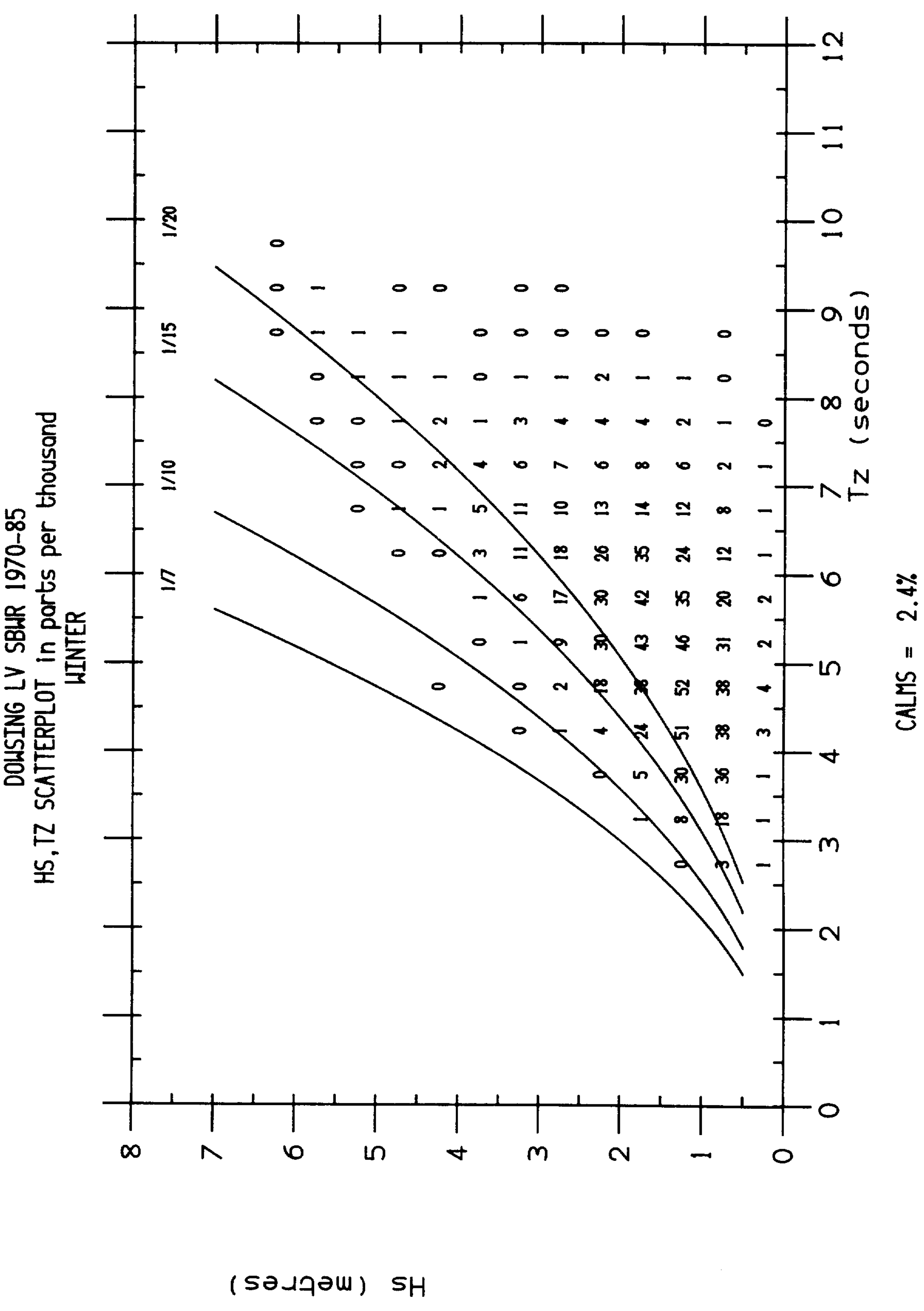

DOWSING LV SBWR 1970-85
HS,TZ SCATTERPLOT in parts per thousand
WINTER
Hs (metres)
Tz (seconds)
1/7
1/10
1/15
1/20
CALMS = 2.4%

Figure 8e

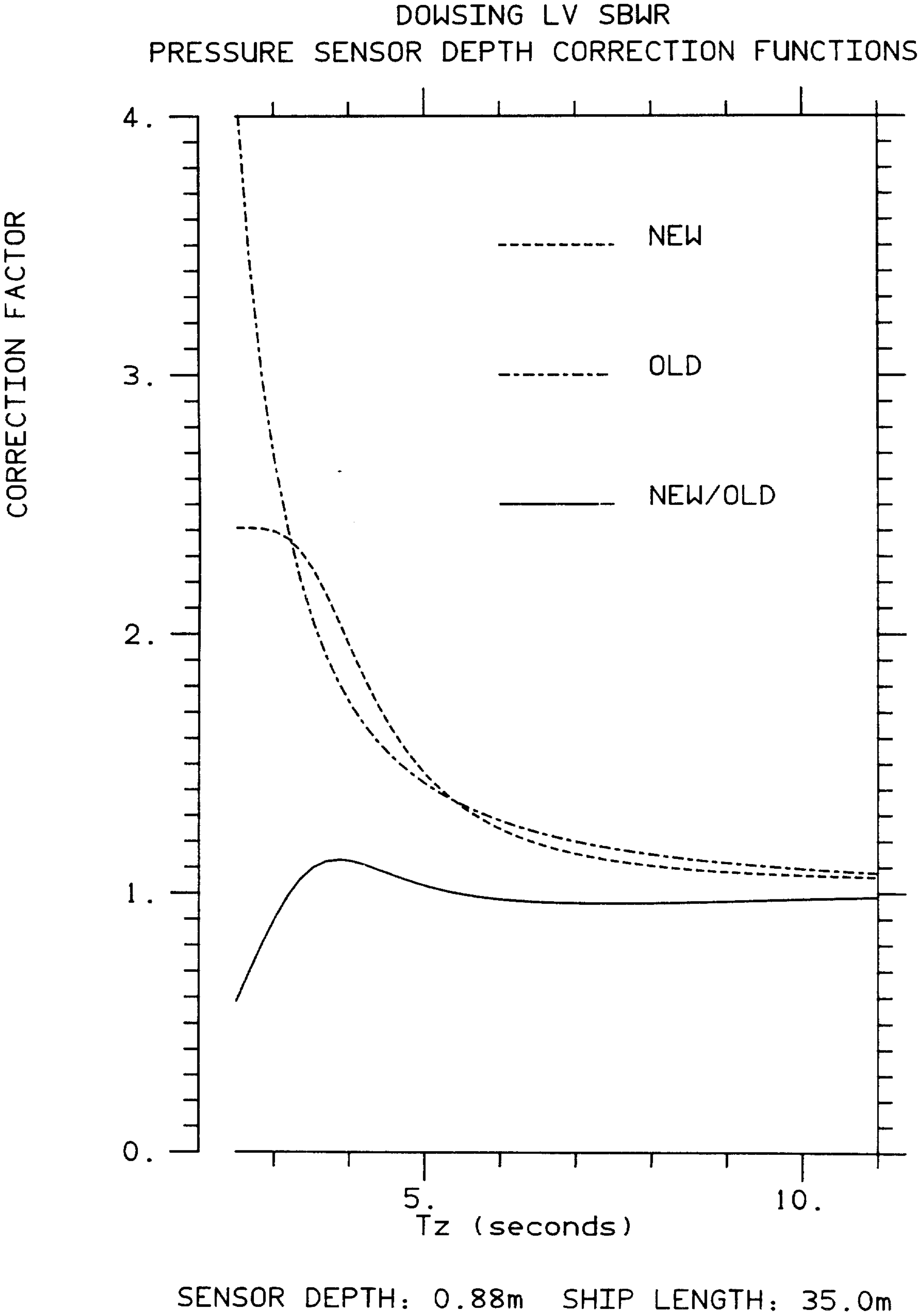

DOWSING LV SBWR
PRESSURE SENSOR DEPTH CORRECTION FUNCTIONS
CORRECTION FACTOR
4.
3.
2.
1.
0.
NEW
OLD
NEW/OLD
5.
10.
Tz (seconds)
SENSOR DEPTH: 0.88m SHIP LENGTH: 35.0m

Figure 9

## 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 $4\sigma$, where $\sigma$ is the standard derivation 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 different forms for the SBWR Marks I and II; the Mark II has an improved high-pass filter. The forms of the responses are given below; for further information see Tucker (1956): Mark I and Crisp (1987): Mark II.

$$C_E(\text{Mk.I}) = 0.83(1 + (8.8\omega)^{-2})^{1.5}$$

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

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 (1988) 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
$A_0 = 0.81027$
$A_1 = 0.50723$
$A_2 = -8.1996$
$A_3 = 35.790$

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 (1988) 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 where $S_{T'Tz}$ 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 Dowsing L.V.,

$$S_{T'Tz} = 1.0076$$

$$S_{SF} = 0.9082$$

See Fig.9 , 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 Dowsing L.V., the only significant change in the new scheme over the old is that for records with $T_z$ between 3 and 5 seconds, $H_s$ is increased by between 5 and 15%.

## 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 $\gamma$ (Euler's constant) = 0.5772...; so the moments estimators given data $X_i$, $1 \le i \le n$, are given by

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

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

where

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

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

and values of $\overline{x}$ 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

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

and substituting for $P_X(x)$ from 3.1 for $\gamma$=1 and 2 leads to

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

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

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 $\nu_1$ and $\nu_2$ 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

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

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

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

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 $\chi^2$ distribution.

FITTING OF FT-1 DISTRIBUTION BY MAXIMUM LIKELIHOOD

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

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

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

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

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

where

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

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, and annual maxima,

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

## APPENDIX IV

### Dowsing Calms 1982 and after

Records for 1982 and after contain a seemingly anomalously large percentage of calms, in comparison with all preceding years. Examination of the original chart records showed that this change was due to the application of an increased calm criterion (a calm record being defined before 1982 as <1 foot/<0.3 m, and for 1982 and after as <0.5 m), and also to a decrease in chart record scale. Also, there was a possibility that the later calm criterion had been applied 'over-generously'. Further, application of the pressure sensor depth correction to these low $H_s$ records, which are also generally of short period, results in an increase of the corrected over the uncorrected $H_s$, which could result in a change in the grouped $H_s$ distribution. It was decided to have all calm records for one year re-analysed to determine what effects would result; for this purpose, 1982 was chosen, having the largest number of calms. Note that in the following discussion, the original form of the pressure sensor depth correction was used.

COMPARISON OF ORIGINAL AND RE-ANALYSED DATA

All original calm records were subjected rigorously to the calm criterion '<½ m'. A new data file was created by replacing all altered records. Table A1 below shows the resulting change in monthly calm totals.

**TABLE A1 - MONTHLY CALM TOTALS**

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calm Total (original) | 34 | 34 | 44 | 68 | 87 | 96 | 73 | 70 | 103 | 67 | 21 | 22 | 719 |
| Calm Total (altered) | 9 | 6 | 29 | 32 | 49 | 56 | 45 | 3 | 26 | 9 | 3 | 3 | 270 |

Six records from 1982, classed as faulty, were found in fact to be valid. Table A2 below shows the resulting change in the grouped $H_s$ distribution for the year; figures given are % of total, except for the last two columns which show the ratio of altered to original total percentages less than ½m and 1 m respectively.

**TABLE A2 - $H_S$ DISTRIBUTIONS (%), 1982**

| | Hs bin (m) | | | | | |
|---|---|---|---|---|---|---|
| | **Calm** | **0-½m** | **½-1m** | **1-1½m** | **(a/O)≤½** | **(a/o)≤1** |
| All data, original | 27.3 | 2.8 | 24.4 | 19.6 | 0.952 | 1.004 |
| All data, altered | 10.4 | 18.2 | 26.1 | 19.5 | | |

For the whole year, 95% of records originally ≤½m remained so (including calms). Broadly, two-thirds of the original calm records were now placed in the bottom $H_S$ bin, and the rest remained as calms.

COMPARISON OF MONTHLY AND ANNUAL STATISTICS

Tables A3 and A4 below give monthly mean and variance for both original and altered files, calculated assuming $H_S$(calm) = 0 m. Also included are means and variances for the original data set calculated assuming $H_S$(calm) = 0.25 m, to see if results are produced which are adequately consistent with the 'correct' altered data set.

**TABLE A3 - MONTHLY MEAN VALUES OF $H_S$**

| **Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\overline{H_S}$(original) $H_S$(calm) = 0 | 1.01 | 1.12 | 1.04 | 0.96 | 0.74 | 0.77 | 0.69 | 0.76 | 0.74 | 1.17 | 1.40 | 1.46 |
| $\overline{H_S}$(altered) $H_S$(calm) = 0 | 1.10 | 1.17 | 1.06 | 1.02 | 0.80 | 0.84 | 0.74 | 0.86 | 0.85 | 1.24 | 1.43 | 1.49 |
| $\overline{H_S}$(original) $H_S$(calm) = ¼m | 1.09 | 1.16 | 1.12 | 1.03 | 0.83 | 0.87 | 0.76 | 0.83 | 0.85 | 1.24 | 1.42 | 1.49 |

## TABLE A4 - MONTHLY $H_s$ VARIANCE

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Var($H_s$)original $H_s$(calm) = 0 | 0.84 | 0.47 | 0.76 | 0.86 | 0.54 | 0.61 | 0.31 | 0.45 | 0.67 | 1.01 | 0.64 | 0.72 |
| Var($H_s$)altered $H_s$(calm) = 0 | 0.70 | 0.36 | 0.67 | 0.77 | 0.46 | 0.53 | 0.27 | 0.34 | 0.55 | 0.87 | 0.57 | 0.64 |
| Var($H_s$)original $H_s$(calm) = $\frac{1}{4}$m | 0.71 | 0.39 | 0.61 | 0.74 | 0.42 | 0.47 | 0.22 | 0.36 | 0.53 | 0.87 | 0.59 | 0.66 |

Generally the monthly mean $H_s$ increases by between 2 and 10%, as one might expect if one-quarter of all $H_s$ records for the year are increased from a nominal value of zero to $\frac{1}{4}$ m. Monthly variances decrease as a consequence of the altered calms being moved closer to the mean $H_s$. The values of mean and variance calculated from the original data set assuming $H_s$(calm) = $\frac{1}{4}$ m were included for comparison with the altered data set; one would expect means and variances from these two to be more similar to each other than either would be to the original data set, if the majority of the original calm records are fairly evenly distributed between 0 and $\frac{1}{2}$ m. For eleven months, $\bar{H}_s$ (altered, calm = 0) and $\bar{H}_s$ (original, calm = $\frac{1}{4}$) are within 0.03 m of each other. The remaining month, March, has the lowest number of calms removed by alteration, and given that $\bar{H}_s$ (original, calm = 0) and $\bar{H}_s$ (altered, calm = 0) are similar, it seems likely that in this case, the calm records were mostly genuinely calm. A similar comparison of $\bar{H}_s$ (altered, calm = 0) and $\bar{H}_s$ (original, calm = 0) shows only 3 months within 0.03 m of each other, the remainder being from 0.05 to 0.11 m different (altered > original).

Two possible methods of treating calms from 1982 and after without re-analysing all 'calms' were considered: (i) to regard all 'calms' as $0 \leq H_s < 1$ m and to group all data of $H_s < 1$ m into one bin. This was rejected, as roughly 50% of all Dowsing data falls into this category, and is distributed within there sufficiently non-linearly such that the ascription of the mid-bin value (0.5 m) as the nominal bin mean (e.g. for fitting cumulative distributions) would have been unacceptably inaccurate; (ii) to regard 'calms' as $0 \leq H_s < 0.5$ for grouped data, and $H_s$ = 0.25 m for individual (e.g. monthly mean) calculations. This would leave one area of anomaly unaccounted for: referring again to Table A2, it can be seen that the net effect of the re-analysis was to move 1.5% of the year's data from $0 \leq H_S < 0.5$ m to $0.5$ m $\leq H_S < 1.0$ m. The effect of this on the mean and variance calculated from the grouped data, assuming $H_S$ for each bin is represented by the mid-bin value, can be calculated as

$$\Delta m = p(h_j - h_i)$$

$$\Delta v = p(h_j^2 - h_i^2) - 2m\Delta m \quad \text{(approx.)}$$

where p is the quantity of probability moved from $h_i$ to $h_j$, m is the original mean and $\Delta m$ and $\Delta v$ are the changes in mean and variance. The original total data mean and variance (grouped data) are 1.065 m and 0.607 m²; $h_i = \frac{1}{4}$ m, $h_j = {}^3/_4$ m, p = 0.015 so that $\Delta m = 7.5 \times 10^{-3}$ m and $\Delta v = -7.5 \times 15^{-3}$ m² so that the adjusted means and variances should be 1.072 and 0.599: as calculated from the adjusted data (grouped) they are 1.070 and 0.596.

This is believed to represent an acceptable margin of error (i.e. ~0.7% of $H_S$, and 1.2% of var($H_S$)), so option (ii) was adopted.